Gearbox Reliability Collaborative Phase 3 Gearbox 3 Test Plan

Jonathan Keller and Robb Wallen
National Renewable Energy Laboratory

Technical Report
NREL/TP-5000-66594
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List of Acronyms

CRB	cylindrical roller bearing
DAS	data acquisition system
fcCRB	full-complement cylindrical roller bearing
GRC	Gearbox Reliability Collaborative
HSS	high-speed shaft
kW	kilowatt
LSS	low-speed shaft
mV/V	millivolts per volt
MW	megawatt
NREL	National Renewable Energy Laboratory
NTL	nontorque load
NWTC	National Wind Technology Center
TRB	tapered roller bearing

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1 Introduction and Background

Many gearboxes in wind turbines do not achieve their expected design life [1]; they do, however, commonly meet or exceed the design criteria specified in current standards in the gear, bearing, and wind turbine industry as well as third-party certification criteria. The cost of gearbox replacements and rebuilds, as well as the downtime associated with these failures, increases the cost of wind energy. In 2007, the U.S. Department of Energy established the National Renewable Energy Laboratory (NREL) Gearbox Reliability Collaborative (GRC). Its goals are to understand the root causes of premature gearbox failures and to improve their reliability [2]. The GRC is examining a hypothesis that the gap between design-estimated and actual wind turbine gearbox reliability is caused by underestimation of loads, inaccurate design tools, the absence of critical elements in the design process, or insufficient testing.

The GRC uses a combined gearbox testing, modeling, and analysis approach. To date, it has focused on a 750-kilowatt (kW) drivetrain, including the dedicated design of a nonproprietary gearbox with cylindrical roller bearings (CRBs) in the planetary section. Two of these gearboxes, GB1 and GB2, were manufactured and tested. Phase-1 and Phase-2 testing focused on planetary section load-sharing characteristics [2]. A major finding was the detrimental effect of rotor nontorque loads (NTLs) on load sharing, predicted fatigue life in high-torque conditions, and the risk of bearing skidding in low-torque conditions [3]. The GRC has disseminated engineering drawings, gearbox models, test data, and results [4], which have facilitated improvements to gearbox design standards and associated modeling tools. More recently, additional dynamometer tests in Phase 3 were conducted [5,6] with additional instrumentation on the high-speed shaft (HSS) and its locating tapered roller bearing (TRB) pair [7,8]. The objective of these tests was to assess HSS TRB load-sharing characteristics with a misaligned generator [9-11] and the potential for roller slipping during transient and grid loss events [12,13].

Simultaneous with the Phase-3 testing on the original GRC gearbox design, there was an interest in redesigning the GRC gearbox to improve its load-sharing characteristics and predicted fatigue life. The redesign was led by Romax Technology with contributions from Powertrain Engineers and The Timken Company (hereafter referred to as Timken) and completed in September 2012. The most important aspect of the redesign was to replace the CRBs with TRBs in the planetary section. Purpose-designed planet gears and bearings, as well as the remainder of the commercial bearings in the gearbox, were supplied by Timken in September 2014. Brad Foote Gearing manufactured the remainder of the gearing and assembled the gearbox in March 2016. This new gearbox is referred to as GB3.

This document describes the test plan for GRC GB3. The primary test objective is to measure the planetary load-sharing characteristics in the same conditions as the original GRC gearbox design. If the measured load-sharing characteristics are close to the design model, the projected improvement in planetary section fatigue life and the efficacy of preloaded TRBs in mitigating the planetary bearing fatigue failure mode will have been demonstrated. Detailed analysis of these test objectives will be presented in subsequent publications.

2 Test Article

The GRC drivetrain was originally designed for a stall-controlled, three-bladed upwind turbine with a rated power of 750 kW [2]. The drivetrain generates electricity at two main shaft speeds, 14.7 rpm and 22.1 rpm. The gearbox ratio of 81.491 converts these main shaft speeds to generator speeds of 1,200 rpm and 1,800 rpm. The drivetrain design follows a conventional configuration in which the main bearing and main shaft, gearbox, and generator are mounted to the bed plate as shown in Figure 1. The main shaft is connected to the gearbox via a shrink disk and the gearbox is connected to the generator via a flexible coupling. Everything but the hub is included in the dynamometer tests. The gearbox is mounted with a three-point configuration in which forces are reacted mostly at the main bearing, whereas rotor moments and torque loads are transferred to the bed plate through two torque arms and rubber bushings. Gearbox motion and the stiffness characteristics of the torque arm rubber bushings and generator coupling were recently characterized [10].

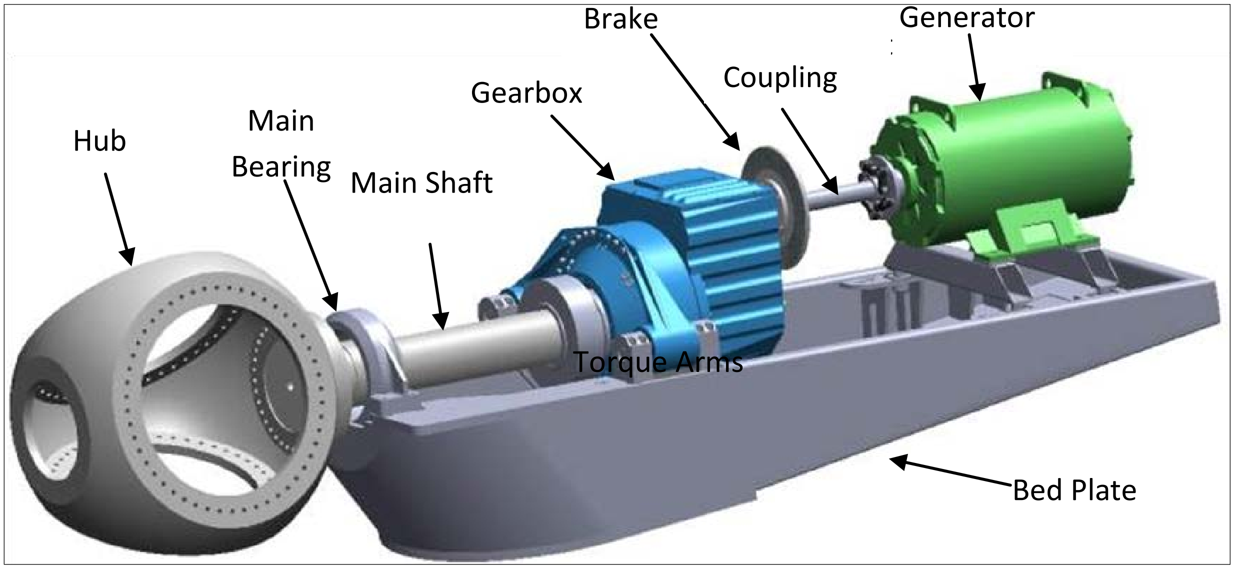

Figure 1. Drivetrain configuration

2.1 Gearbox

The GRC gearboxes are composed of one low-speed planetary stage with three planet gears and two parallel shaft stages as shown in Figure 2. The housing components of the original Jahnel-Kestermann PSC 1000-48/60 commercial gearboxes were retained, but the majority of the internal components were redesigned and newly manufactured for all of the GRC gearboxes. The GRC gearboxes feature a floating sun configuration to equalize the load distribution among the planets. To accommodate the floating sun arrangement, the low-speed shaft is hollow and has an internal spline connection that transfers the torque to the parallel-shaft stages.

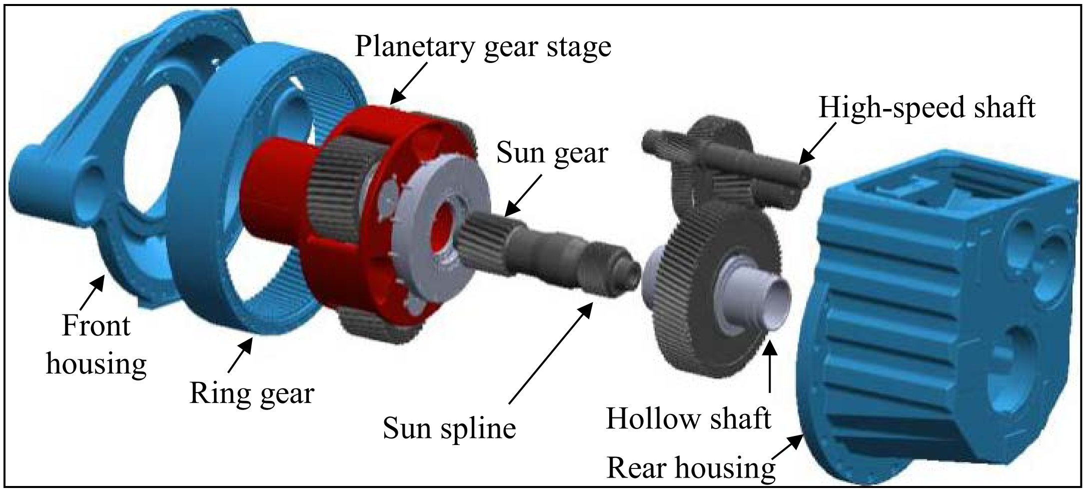

Figure 2. Gearbox configuration. *Illustration by Powertrain Engineers Inc.*

A tradeoff study was completed for the GB3 design to determine what planetary system changes had the most beneficial impact on predicted fatigue life [14-17]. After a down-selection process, which considered cost and schedule impacts, the following key improvements were selected for GB3 resulting in a projected increase of three times the planetary section fatigue life compared to the original design [18]:

- Preloaded planet carrier and planet TRBs, and stiffer planet pins to improve alignments in the planetary system and improve the load-sharing characteristics
- Planet TRB outer races integral to the planet gears to increase capacity and eliminate outer race fretting

Additional design changes were also made to facilitate the key improvements, or otherwise improve assembly or operation of the gearbox. Although valuable, the following changes are not part of the test verification process:

- A robust bolt system between the ring gear and front and rear housings to accommodate increased axial loads from the planetary system
- A ring gear nitrided to improve fatigue life. The ring gear is also 29 mm longer to improve ease-of-assembly of the central plate and allow more space for the TRBs and the new oil feed ring system. This change necessitated shifting the generator aft by the same amount by enlarging the mounting holes in the generator-mount cross members
- The spline coupling crowning was reduced by 50% to increase the load-carrying area of the spline without negatively affecting system life or gear alignment.
- Hollow shaft bearings in an X-arrangement with tighter inner races to reduce fretting
- An improved, semidry sump lubrication system with improved delivery to the planet bearings, planet gears, and HSS TRBs.

A comparison of the key design characteristics of both GRC gearbox designs is shown in Figure 3.

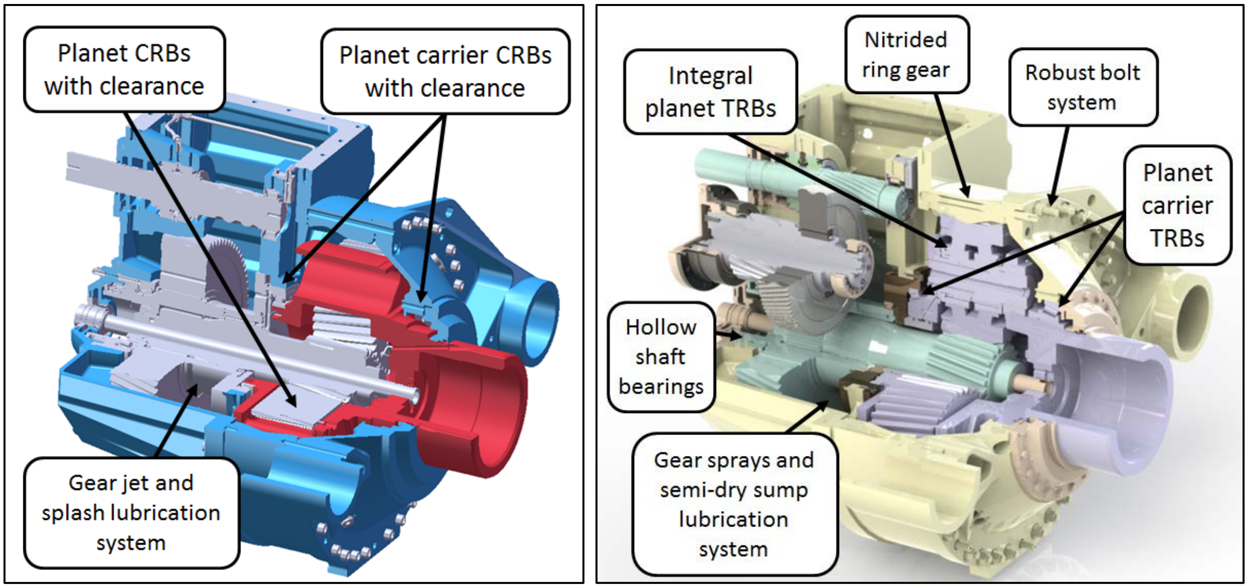

Figure 3. Comparison of gearbox 2 (left) and 3 (right) design characteristics. *Illustration by Romax Technology (right)*

2.1.1 Gear Arrangements

The arrangement and basic gear geometries of GB3 are largely the same as GB2 [5]. Although the ring gear was widened, the sun and planet face widths remain the same.

2.1.2 Bearing Arrangements

The bearing types and arrangements are the primary differences between GB2 and GB3 as listed in Table 1. The full-complement CRB (fcCRB) supporting the planet carrier (PLC) has been replaced by TRBs, and the CRBs supporting each planet have been replaced by integral TRBs. The low-speed shaft (LSS), intermediate-speed shaft (ISS), and HSS bearing arrangements are typically similar although the exact designations may have changed. The letter following the location abbreviation indicates the position of the bearing from upwind (A) to downwind (B – rotor side, C – generator side). All bearings for GB3 were supplied by Timken.

Table 1. Bearing Type Comparison

Bearing	GB2		GB3	
	Type	Designation	Type	Designation
PLC-A	fcCRB	SL 18 1892E	TRB	EE244180-90040
PLC-B	fcCRB	SL 18 1880 72/K10	TRB	L865547-902A3
PL-A/B	CRB	NJ2232EM1C3	TRB	NP527934
LSS-A	fcCRB	SL 18 1856E	CRB	NU1856EMA
LSS-B/C	TRB	32948	TRB	JP24049-90xxx
ISS-A	CRB	NU2220EM1C3	CRB	NU2220EMA
ISS-B/C	TRB	32032X	TRB	32032XM-90NM4
HSS-A	CRB	NU2220EM1C3	CRB	NU2220EMA
HSS-B/C	TRB	32222 J2	TRB	32222M-90xxx

A gearbox internal and planet TRB schematic is shown in Figure 4. The planet-gear bore was specially designed as it also serves as the planet-bearing outer race. The planet-bearing bore was also specially designed as it contains special grooves for instrumentation and wire routing. Both the planet gears and planet bearings, shown in Figure 5, were manufactured, instrumented, and calibrated by Timken.

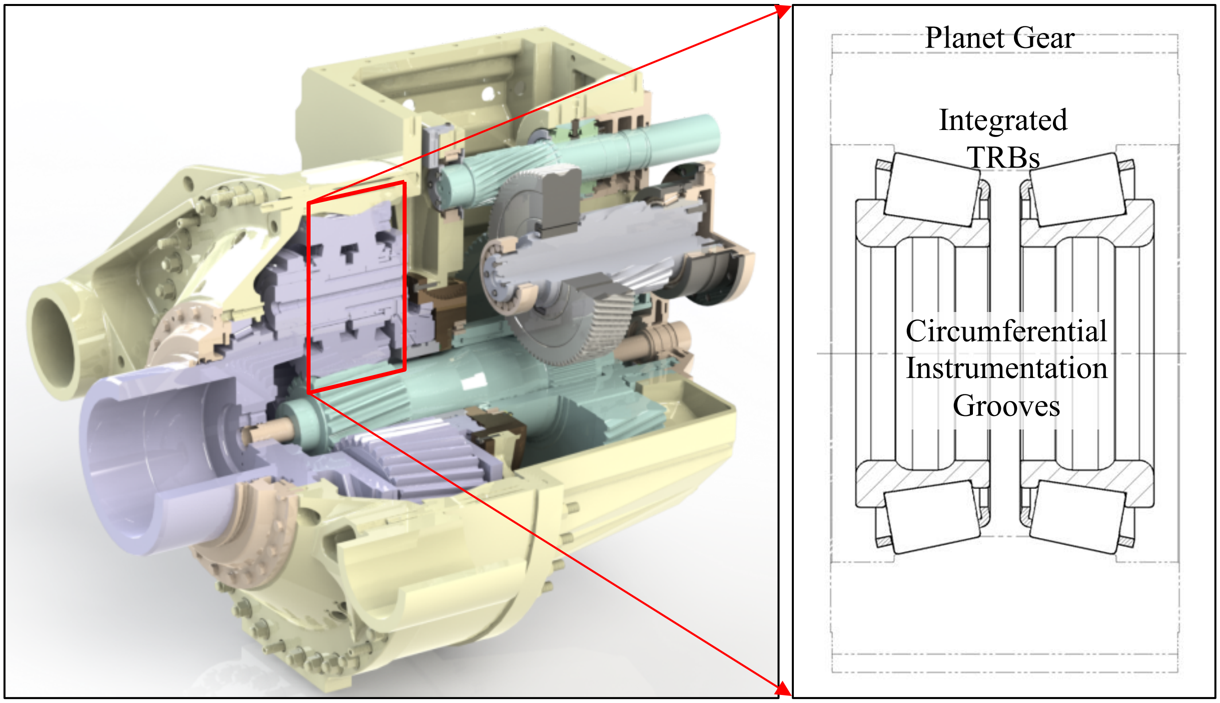

Figure 4. Gearbox 3 planet bearings. *Illustrations by Romax Technology (left) and Timken (right)*

Figure 5. Planet bearings and gears. *Photos by Jonathan Keller, NREL 36523, 36524, and 36520*

3 Test Environment

The National Wind Technology Center (NWTC) 2.5-megawatt (MW) dynamometer test facility [19] will be used for GB3 testing. Prior installation of the GRC drivetrain with GB2 is shown in Figure 6. The dynamometer variable frequency drive was upgraded to an ABB ACS2000 drive [20], which is an enabling factor for the reproduction of field conditions. The new drive uses a voltage source converter topology, enabling dynamic torque control via Profibus DP up to a bandwidth of 250 hertz (Hz). The NTL system, also shown in Figure 6, is used to apply thrust, vertical force, lateral force, pitch moment, and yaw moment. Given the fixed distance between the NTL application point and the GRC main bearing, the relationship between the vertical and lateral forces and the resulting pitch or yaw moments is fixed and cannot be controlled independently. The NTL system can apply loads statically or dynamically up to approximately 10 Hz, depending on force and hydraulic flow volume requirements.

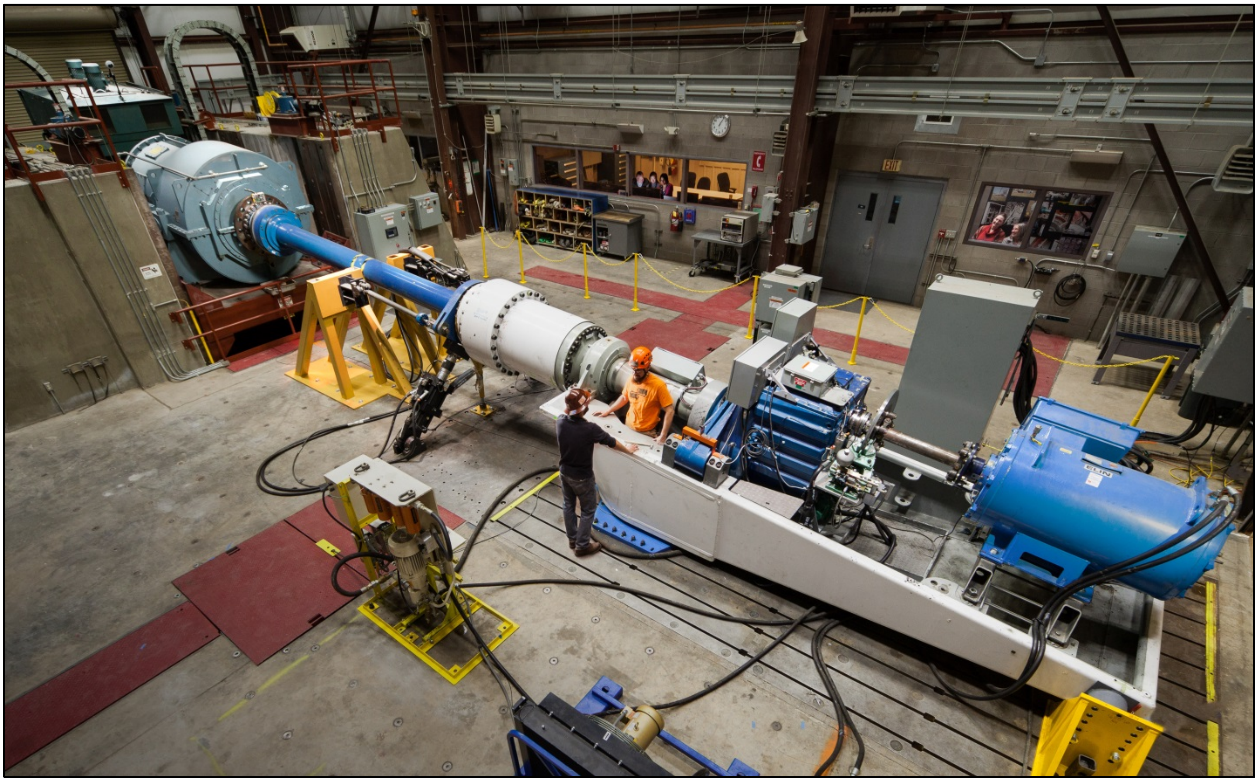

Figure 6. GRC setup. *Photo by Mark McDade, NREL 32734*

The mechanical and electrical connections to the dynamometer facility and generator cooling system are the same for GB3 as Phase 3 testing of GB2. Modifications were made to the external lubrication system to accommodate the gearbox sprays, semidry sump and an oil particle counter. Schematics of these systems are shown in Figure A-1 to Figure A-3 in Appendix A.

The data acquisition system (DAS) is based on the National Instruments (NI) deterministic Ethernet platform. One set of chassis process rotating planetary section signals and are mounted in an enclosure on the main shaft. The output of that system is converted to fiber optic and sent across a fiber-optic rotary joint to the nonrotating frame. On the side of the bed plate, a second set of chassis process the HSS signals and other fixed frame signals.

4 Instrumentation

Instrumentation for Phase 3 testing of GB3 can be categorized by location of the sensor. General descriptions of the sensors are provided in this section. Only the gearbox instrumentation has been updated for GB3. The dynamometer, nontorque loading (NTL) system, main shaft, controller, and lubrication system are identical to those measured during previous GB2 tests. Descriptions for all instrumentation are included in this section for completeness.

- Dynamometer
- Nontorque loading system
- Main shaft
- Gearbox
    - Housing
    - Ring gear
    - Planet carrier
    - Planet gears
    - Planet bearings
    - Sun gear
    - Low-speed shaft bearings
    - Intermediate-speed shaft bearings
    - High-speed shaft
    - High-speed shaft bearings
- Lubrication system
- Controller.

Timken installed the planet-bearing instrumentation whereas Romax Technology installed the internal gearbox instrumentation during the gearbox assembly at Brad Foote Gearing. The remaining external gearbox instrumentation was installed by Romax Technology at the NWTC after the gearbox was delivered. Appendix B contains a list of all sensors and resulting signals, and Appendix C provides details on sensor installation and wiring.

4.1 Dynamometer

The dynamometer output torque (signal name Dyno_Torque) is measured with a custom torque spool located on the dynamometer gearbox output flange. This measurement device is more accurately calibrated than the torque gauges on the GRC main shaft, but it does not account for friction in the NTL bearing or the GRC main bearing. The dynamometer output speed (Dyno_Speed) is measured with an encoder mounted on the dynamometer motor and then translated to speed with the dynamometer gearbox ratio.

4.2 Nontorque Loading System

The nontorque loading system has three actuators, each of which has a load cell (signal names NTL_Port_Force, NTL_Star_Force, and NTL_Thrust_Force) and a displacement sensor (signal names NTL_Port_Disp, NTL_Star_Disp, and NTL_Thrust_Disp). The thrust actuator is offset from the center of the shaft; therefore, its load is balanced by a linkage which also features a load cell. Hydraulic pressure to the actuators is monitored using a pressure transducer; however, it is not recorded as part of the test data. System safety limits are set up to automatically remove the NTL loads.

4.3 Main Shaft

The main shaft signals for GB3 are identical to those measured during previous GB2 tests. Torque (signal name LSS_TQ) is measured on the main shaft with a full strain gauge bridge as shown in Figure C-1. A shaft encoder on the aft end of the conduit tube measures shaft rotational position (LSS_Azimuth) and shaft period (signal name LSS_Period) as shown in Figure C-2. The DAS is configured to calculate main shaft speed (signal name LSS_Speed) from the measured shaft period. Main shaft bending (signal names MSBM_YY and MSBM_ZZ) is measured in orthogonal directions as shown in Figure C-3 and Figure C-4. The DAS was also configured to calculate the total main shaft bending moment (signal name MSBM), and fixed-frame bending moments (signal names MSBM_yy and MSBM_zz), from the measured bending moments in the rotating frame and the main shaft azimuth. The total and fixed-frame moments are useful to set desired testing conditions using the NTL system.

4.4 Gearbox

Measurement of the gearbox response, in terms of loads, motions, and temperatures, is important in validating modeling assumptions and methods. The instrumentation on GRC GB3 is tailored to measuring the performance of the TRBs and planetary load sharing, but there are other useful instruments in other parts of the gearbox.

4.4.1 Housing

Measurement of GB3 housing motions relative to the mainframe in six degrees of freedom is identical to that measured during previous GB2 tests. Gearbox axial motion measurements (signal names Trunion_X_port and Trunion_X_stbd) are shown in Figure C-5, lateral-motion measurement (signal name Trunion_Y_) is shown in Figure C-6, vertical-motion measurements (signal names Trunion_Z_stbd and Trunion_Z_port) are shown in Figure C-7, and pitch-motion measurement (signal name Trunion_My_bottom) is shown in Figure C-8.

Internal to the housing of GB3 are three new strain measurements of the structure supporting the downwind end of the planet carrier (signal names WEB_STRAIN_0, WEB_STRAIN_45, and WEB_STRAIN_315) supporting the planetary section as shown in Figure C-9. Modeling of the gearbox during the design process showed high levels of strain in this location due to increase in the planet gear thrust forces.

4.4.2 Ring Gear

Measurement of ring gear tooth-bending strain in GB3 is similar to GB2. But, these measurements have some key differences for both the internal and external measurements to improve the correlation between measurements and simulation models.

Like GB2, the ring gear of GB3 has strain gauges mounted in the root of the internal teeth, which are arranged to sense tooth-bending strain. These strain gauges are located at three equally spaced circumferential locations—0° (top of the ring gear), 120°, and 240°—at eight places along the tooth face width in each location. GB2 has the eight strain gauges mounted in two separate bridge configurations with four teeth between each adjacent gauge so that each bridge spans 12 ring gear teeth. Because the ring gear has 99 teeth, the bridge spans nearly 45° at each location. That is, the strain gauges for the 0° circumferential location start between tooth 1 and 2 at 0° and end between tooth 13 and 14 at almost 45°. This is a relatively wide spacing to assess the face width load distribution and really represents the average tooth strain over the 45° span. Instead, on GB3, the eight strain gauges are separately measured signals. Therefore, the gauges can be located in adjacent tooth roots to get a much more accurate measurement of the face width load distribution on that particular ring gear location. Installation in adjacent roots is the minimum, because space within the root is also needed for wiring. These measurements are shown in Figure C-10 for the 0° location (signal name INT_KHB_0_), Figure C-11 for the 120° location (signal name INT_KHB_120_), and Figure C-12 for the 240° location (signal name INT_KHB_240_).

Also, like GB2, the ring gear of GB3 has strain gauges mounted on the exterior face of the ring gear. However, GB2 only had them at one circumferential location and they were incorrectly placed. GB3 has the external gauges mounted directly over the internal gauges at all three circumferential directions (signal names EXT_KHB_0_, EXT_KHB_120_, and EXT_KHB_240_) as shown in Figure C-13 to Figure C-15. This method will yield the most direct correlation between internal and external ring gear measurements.

4.4.3 Planet Carrier

Proximity sensors indicate the radial motion at two positions (signal names Radial_040 and Radial_310) and axial motion at four positions (signal names Carrier_047, Carrier_137, Carrier_227, and Carrier_317) of the planet carrier relative to the housing as shown in Figure C-16 and Figure C-17. This motion is a combination of rigid body motion and deformation of the carrier and housing. These sensors are mounted on the upwind face and sides of the gearbox housing using a custom fitting that bolts to the housing. These measurements are identical to GB2.

4.4.4 Planet Gears

Planet gear sensors include six proximity sensors that are mounted on the carrier in an identical manner as GB2. These measure the positions of two of the planets (B and C) relative to the carrier (signal names PlanetB_RIM_ and PlanetC_RIM_). Each set of three sensors is mounted identically as shown in Figure C-18 and Figure C-19. These indicate both axial motion and tilting of the planetary gears.

4.4.5 Planet Bearings

The most significant change in instrumentation between GB2 and GB3 is within the planet bearings. GB2 and GB3 have the same number of planet-bearing load measurements; however, the planet bearings for GB2 are instrumented with the same number of measurements whereas one set of planet bearings of GB3 is much more highly instrumented than the other two sets. This change was made to provide more detailed information on the load zone.

Each set of GB2 planet bearings has strain measurements at only three circumferential locations, so only a coarse description of the planet-bearing load zone can be made. However, there are two axial measurements for each bearing, so the axial load distribution was well measured and has been studied intensively [3]. This yields 36 planet-bearing strain measurements for GB2.

As stated earlier, the primary design change to GB3 is the use of TRBs to support the planets to improve load sharing. Therefore, the planet B bearing set of GB3 has measurements at 10 circumferential locations (signal names PlanetB_LOAD_) to measure the load-zone distribution. The other two planet-bearing sets (A and C) have measurements at only four circumferential locations (signal names PlanetA_LOAD_ and PlanetC_LOAD_). For the complete gearbox, this again results in 36 strain measurements. The measurement locations for all three planets are summarized in Table 2 and shown in Figure C-20 to C-22. Additionally, two thermocouples were mounted in the grooves of each planet bearing to measure inner race temperatures (signal names PlanetA_TEMP_, PlanetB_TEMP_, and PlanetC_TEMP_) as shown in Figure C-23.

Table 2. Planet-Bearing Sensor Locations

Planet	Bearing	GB2 Locations (clockwise from top dead center)	GB3 Locations (clockwise from top dead center)
A	Upwind (PL-A)	2 axial locations at 0°, 86°, and 274°	1 axial location at 70°, 160°, 250°, and 340°
	Downwind (PL-B)	2 axial locations at 0°, 86°, and 274°	1 axial location at 20°, 115°, 200°, and 285°
B	Upwind (PL-A)	2 axial locations at 0°, 256°, and 308°	1 axial location at 10°, 32°, 70°, 160°, 250°, 288°, 310°, 327.5°, 340°, and 352.5°
	Downwind (PL-B)	2 axial locations at 0°, 256°, and 308°	1 axial location at 7.5°, 20°, 32.5°, 50°, 77°, 115°, 200°, 285°, 323°, and 350°
C	Upwind (PL-A)	2 axial locations at 0°, 290°, and 334°	1 axial location at 70°, 160°, 250°, and 340°
	Downwind (PL-B)	2 axial locations at 0°, 290°, and 334°	1 axial location at 20°, 115°, 200°, and 285°

4.4.6 Sun Gear

Two proximity sensors indicate the radial position of the sun gear relative to the planet carrier as shown in Figure C-24. They sense the upwind end of the sun shaft in the area that extends about 50 mm beyond the end of the sun pinion. These sensors record this motion relative to the carrier in two orthogonal directions (signal names Sun_radial_YY and Sun_radial_ZZ). These measurements are identical to GB2.

4.4.7 Low-Speed Shaft Bearings

New to GB3 is the measurement of the outer ring temperature of the downwind TRB supporting the LSS (signal name TEMP_LSS_DW_BRG) as shown in Figure C-25. Challenges in delivering lubrication to these bearings necessitated temperature monitoring.

4.4.8 Intermediate-Speed Shaft Bearings

Also new to GB3 is the measurement of the outer ring temperature of the downwind TRB supporting the intermediate-speed shaft (signal name TEMP_ISS_DW_BRG), as shown in Figure C-26, for similar reasons as the LSS bearing.

4.4.9 High-Speed Shaft

In Phase 3, the HSS instrumentation of GB2 was significantly enhanced. Strain gauges measured pinion loads, shaft torque, shaft bending, and TRB loads. Other sensors measured bearing temperatures, and an encoder measured shaft speed and azimuthal position.

Some of this instrumentation was repeated for GB3, and some new instrumentation was added. Shaft bending moments at three locations along the shaft, and torque at one location (signal name HSS_TQ), were again measured (Figure C-27 to Figure C-29). Both the inner and outer ring temperatures of the TRBs (signal names TEMP_HSS_TRB_IR_ and TEMP_HSS_TRB_OR_) are monitored as shown in Figure C-30 and C-31. The sensors mounted to the shaft are routed through a slip ring installed on the upwind end of the shaft as shown in Figure C-32. The HSS encoder is shown in Figure C-33. The DAS was configured to calculate the HSS speed (signal name HSS_Speed) from the measured HSS period. Similar to GB2, the measured shaft position (signal name HSS_Azimuth) has a 60º offset because of the position of the mounting bracket that must be subtracted from all measured azimuth values to align with the reference mark on the HSS shown in Figure C-27 to Figure C-29. In this manner, the reference mark on the HSS is pointing up at 0º. The pinion loads and TRB loads are not measured for GB3.

4.5 Lubrication System

The lubrication system is monitored using a variety of sensors. Most of the sensors are external to the drivetrain and are shown in Figure A-3 in Appendix A. They include the speed of the oil cooler fan (signal name Lube_Fan_Speed); the total flow rate, including bypass at the lubrication system pump and flow rate to the gearbox (signal names Lube_Flow_Pump and Lube_Flow_Meter); the pressure at the distribution manifold (signal name Lube_Manifold_Pressure); and the temperature at the distribution manifold (signal name Lube_Manifold_Temp). The temperature at the outlet of the gearbox sump (signal name Sump_Temp) is also monitored as shown in Figure C-34. In addition to basic lubrication system performance characteristics, the oil cleanliness is monitored with a Hydac CSM 1220 oil particle counter and reported in accordance with ISO 4406 (signal names ISO_1, ISO_2 and ISO 3).

4.6 Controller

Relays indicate the status of the generator's electrical connection to the grid—one relay for the high-power generator windings, one for the low-power generator windings, and one to indicate when the soft-start components are bypassed as shown in Figure A-2 in Appendix A (signal names Controller_g_contactor, Controller_G_contactor, and Controller_bypass_contactor). A power meter indicates real and reactive power at the connection of the generator to the grid (signal names kW and KVAR).

4.7 Signal List

The data will be recorded in two separate data streams by acquisition rate. A 100- Hz rate will be used to record information on the planetary and intermediate sections of the gearbox. A 2,000-Hz rate will be used to record information on the high-speed section of the gearbox. In each data stream, relevant signals related to the input loading conditions, lubrication system, or output performance of the generator and controller will also be recorded. The signals included in each data stream are listed in Table B-1 and Table B-2 in Appendix B, for the 100-Hz and 2,000-Hz rates, respectively. The overwhelming majority of signals will be recorded in the engineering units of interest; however, the planetary section and HSS section strain gauges will be recorded in native units of millivolts per volt (mV/V). The data files will be named beginning with the convention “Test Type_,” derived from the name of a particular test in the test plan such as “Static_NTL.” “Test Sequence_” follows Test Type and corresponds to sequences in the test plan such as “5A.” Finally, the data file names will be appended with “YYYY_MM_DD_HH_SS_ZZZZHz.tdms,” where YYYY, MM, DD, HH, and SS are the year, month, date, hour, and second of the data acquisition, respectively, and ZZZZ is the acquisition rate in hertz.

5 Test Sequence

Testing of GB3 in Phase 3 will consist of the following major test sequences:

- Drivetrain recommissioning
- NTL tests
- HSS radial misalignment tests
- Field representative tests
- Variable speed tests.

For each of the tests, physical, continuous limits are specified in Table 3, supported by additional documentation of gearbox mechanical safety factors. During the testing, if any of the limits are exceeded, the gear tooth surfaces should be inspected for abrasive wear and contact fatigue.

Table 3. Dynamometer Test Limits

Item	Minimum	Maximum
Drivetrain Electrical Power	-	800 kW
Shaft Speed	-	22.5 rpm (main shaft) 1,833 rpm (HSS)
Dynamometer Torque	-	400 kNm
Rotor Moment	-300 kNm	300 kNm
Oil Supply Pressure	21.5 psi/1.5 bar	29 psi/2 bar
Oil Supply Temperature	45°C	55°C
Bearing Temperature	-	80°C
Oil Sump Temperature	45°C	70°C

5.1 Drivetrain Commissioning

The drivetrain commissioning test sequence will ensure that the dynamometer controls, drivetrain, gearbox, and instrumentation are all operating normally and ready for full-load testing. GB3 must first undergo flushing, followed by a break-in sequence during which the sensors and controls can be verified. These commissioning tests are used to gradually increase speed, torque, and nontorque loads, with frequent checks to ensure acceptable control and data-acquisition performance.

5.1.1 Gearbox Flushing

The purpose of flushing the gearbox is to remove contaminants that might have been left over from the manufacturing and assembly process. This prevents damage to the gears and bearings from debris during the following run-in process. The lubrication system has two sets of parallel filters. The filter bypass indicators should be monitored throughout the flushing process and the filters replaced as needed. The lubrication return line will has an oil particle counter that measures cleanliness and reports values in an ISO 4406 classification.

The sequence for gearbox flushing is:

- Fill the gearbox with 16 gallons (60 liters), the external lubrication tank with 43 gallons (160 liters), and the lubrication lines with 5 gallons (20 liters) of ISO VG 320 lubrication oil. The oil shall be -/14/11 prior to entering the system.
- Heat lubricant to 45°C – 55°C with immersion heaters to achieve correct viscosity.
- Flush the lubrication oil through the gearbox, small particle filter, and oil particle counter until it reaches -/14/11. This may require 4 to 8 hours.
- Using the dynamometer, spin the gearbox at low speed (5% to 10% rated speed or 1 to 2 rpm). Continue flushing the gearbox until the lubrication oil reaches -/14/11. This may require 4 to 8 hours.
- At this point, the flushing process is complete. Inspect and replace the oil filters as necessary.

5.1.2 Gearbox Run-In

The objective of "running in" the gearbox is to reduce the roughness of mating surfaces created by the manufacturing process. To successfully break-in the gearbox, the surface roughness must be gently worn down. Oil cleanliness, vibration, pressure, and temperatures of bearings and lubrication oil must be continuously monitored during the run-in process. If bearing temperatures are elevated, stop the run-in and determine the cause before continuing. The lubrication system filter bypass indicators should be monitored and the filters replaced, as needed, during the test.

The gearbox run-in process is listed in Table 4. The data specified in Table B-1 in Appendix B should be collected throughout the sequence, but a rate of 10 Hz is sufficient. Data recording can be paused if the dynamometer is stopped. At each load step, the oil sump and bearing temperatures must stabilize within 0.5°C in a 5-minute period and the oil cleanliness level must be better than -/15/12. After stabilization, the gearbox must be run for an additional 30 minutes before proceeding to the next step. Once stabilized, each load level is maintained for the specified duration. When the sequence has been completed, replace all oil filters.

Table 4. Gearbox Run-In Procedure

Step	Torque (%/kNm)	Drivetrain Speed (%)	Main Shaft Speed (rpm)	HSS Speed (rpm)	Duration* (hr)
1	5/18	30	6.6	540	1
2	5/18	66.7	14.7	1,200	1
3	5/18	100	22.1	1,800	1
4	20/72	100	22.1	1,800	1
5	40/144	100	22.1	1,800	1
6	60/216	100	22.1	1,800	1
7	80/288	100	22.1	1,800	1
8	100/360	100	22.1	1,800	1

*Each load step should be run to stabilization plus 30 minutes for a minimum of 1 hour.

5.1.3 *High-Speed Shaft Torque Investigation*

In previous testing of GB2, a periodic ±10% variation in the HSS torque was measured—even in offline conditions [6,10]. A possible source for this variation has been hypothesized as tooth spacing errors on the high-speed pinion [21]. Because the high-speed pinion was newly manufactured for GB3, there is an opportunity to examine this hypothesis by repeating previous GB2 testing.

In this test, acquire the data specified in Table B-1 and Table B-2 in the conditions listed in Table 5 for direct comparison to GB2 data.

Table 5. HSS Torque Investigation Tests

Power (%/kW)	Drivetrain Speed (%)	Main Shaft Speed (rpm)	HSS Speed (rpm)
Offline	16.7	3.7	300
Offline	33.3	7.4	600
Offline	50	11.0	900
Offline	66.7	14.7	1,200
12%/90	66.7	14.7	1,200
25%/188	66.7	14.7	1,200
Offline	83.3	18.4	1,500
Offline	100	22.1	1,800
25%/188	100	22.1	1,800
50%/375	100	22.1	1,800
75%/563	100	22.1	1,800
100%/750	100	22.1	1,800

5.2 Nontorque Load Tests

Phase 3 testing of GB3 will repeat the sequence of NTL tests for direct comparison to GB2 with the addition of additional data acquisitions at high NTL levels to assess data repeatability. The NTL tests will proceed from simple static bending moments (gradually increasing in NTL magnitude and drivetrain power), through simple dynamic bending moments, to static thrust load testing. The following sections describe each test series.

5.2.1 *Static Bending Moment*

Static bending moment tests for GB3 will be conducted in offline conditions (sequences 1–3), and at 25% power (sequence 4), 50% power (sequence 5), 75% power (sequence 6), and 100% power (sequence 7) conditions. Similar to testing on GB2, additional test data will be acquired at 10% power in a final sequence (sequence 8). The operating conditions for these sequences are summarized in Table 6, which also references specific NTL loading conditions specified in Table 7.

At each test point, acquire the data specified in Table B-1 and Table B-2.

For all cases, the zero-bending-moment condition is achieved while operating the drivetrain at the desired speed and torque. The NTL system is then used to apply loads to reduce both measured rotating bending moments to nearly the same value, then using the DAS to zero those values. In other words, the actual main shaft bending moment must be zero when the measured rotating moments are both equal and zeroed. This is the tared condition for the drivetrain. When tared, the pitching moment caused by the weight of the dynamometer couplings and shafting has been removed from the drivetrain. The main shaft moments listed below are the desired fixed-frame bending moments to be achieved during the test.

Table 6. Static NTL Tests

Test Number	Power (%)	Speed (%)	Rotation Direction	NTL Sequences
1	Offline	5.5	Normal	A1,H1
2	Offline	5.5	Reverse	A1,H1
3	Offline	100	Normal	All
4	25	100	Normal	All
5	50	100	Normal	All
6	75	100	Normal	All
7	100	100	Normal	All
8	10	100	Normal	A1,H1

Table 7. Static NTL Sequences

NTL Sequence	Myy (kNm)	Mzz (kNm)	Increment (kNm)
A1	-300 to 300	0	100
B	-300 to 300	-100	100
C	-300 to 300	-200	100
D	-300 to 300	-300	100
A2	-300 to 300	0	100
E	-300 to 300	100	100
F	-300 to 300	200	100
G	-300 to 300	300	100
A3	-300 to 300	0	100
H1	0	-300 to 300	100
H2	0	300 to -300	100

5.2.2 Dynamic Bending Moment

Identical to Phase 3 testing of GB2, dynamic bending moment tests for GB3 will be completed in offline (sequence 1), 25%-power (sequence 2), and 100%-power (sequence 3) conditions. The operating conditions for these sequences are summarized in Table 8, which also references specific NTL loading conditions specified in Table 9.

At each test point, acquire the data specified in Table B-1 and Table B-2.

Table 8. Dynamic NTL Tests

Test Number	Power (%)	Speed (%)	NTL Sequences
1	Offline	100	All
2	25	100	All
3	100	100	All

Table 9. Dynamic NTL Sequences

NTL Sequence	Myy (kNm)	Mzz (kNm)	Frequency (Hz)
A	0 to -50	0	2
D	0 to -200	0	2
G	0	0 to 50	2
R	0	-100 to 100	2

5.2.3 Static Thrust

Static thrust testing test sequences will be completed in offline mode (sequence 2), at 25%-power (sequence 3), 50%-power (sequence 4), 75%-power (sequence 5), and 100%-power (sequence 6) conditions as listed in Table 10. For each case, the NTL system is used so there was no measured main shaft bending moment. Nine acquisitions are made for each power setting.

At each test point, acquire the data specified in Table B-1 and Table B-2.

Table 10. Static Thrust Tests

Test Number	Power (%)	Speed (%)	Thrust (kN)	Increment (kN)
2	Offline	100	0 to -100 to 100 to 0	50
3	25	100	0 to -100 to 100 to 0	50
4	50	100	0 to -100 to 100 to 0	50
5	75	100	0 to -100 to 100 to 0	50
6	100	100	0 to -100 to 100 to 0	50

5.3 Generator Misalignment Tests

In Phase 3 testing of GB2, the generator was misaligned up to 3° to assess whether excessive loads were imparted onto the HSS bearings. Analysis showed that the relatively compliant generator coupling had no effect on the HSS loads on either side of the pinion. In the portion of the HSS downwind of the locating bearing pair, the generator misalignment actually acted to relieve the effect of the brake disk weight [11].

In Phase 3 testing of GB3, the only new instrumentation on the HSS is for bearing temperature on the inner and outer rings of the TRB pair. In this testing, measuring the temperature difference in misaligned conditions is the primary purpose of this test. The aligned and maximum misalignment (3º) conditions are tested. Data will be acquired in offline mode (sequence 1 and 2), at 25%-power (sequence 3), 50%-power (sequence 4), 75%-power (sequence 5), and 100%-power (sequence 6) conditions listed in Table 11.

At each test point, acquire the data specified in Table B-1 and Table B-2. For each case, the drivetrain and NTL system are in the untared condition. That is, the NTL system is not used, resulting in a pitching moment of approximately 70 kNm as a result of the weight of the dynamometer shafting.

Table 11. Generator Misalignment Tests

Test Number	Power (%)	Speed (%)	Misalignment (°/mm)
1	Offline	5.5	0/0 and 3°/32.06
2	Offline	100	0/0 and 3°/32.06
3	25	100	0/0 and 3°/32.06
4	50	100	0/0 and 3°/32.06
5	75	100	0/0 and 3°/32.06
6	100	100	0/0 and 3°/32.06

5.4 Field Representative Tests

Reproduction of field conditions in the dynamometer was achieved in Phase 3 testing of GB2 using the dynamometer variable frequency drive capability. The same normal power production and shutdown cases tests will be repeated for GB3.

5.4.1 Normal Power Production

Identical normal power production cases representing 5-m/s, 15-m/s, and 25-m/s wind speed case will be repeated. In each case, a system identification test will be performed in which the desired dynamic torque is commanded and the actual torque is measured. This measured response is then used to tailor the commanded dynamic torque to result in a main shaft torque close to the values measured in the field. The NTLs will be operated in force-feedback mode. The test for each wind speed case lasts 11 min, including a 30-s ramp-up period to full load at the beginning of the test and a 30-s ramp-down period at the end of the test.

At three test points in the sequence, acquire the data specified in Table B-1 and Table B-2.

5.4.2 Shutdown

The GRC drivetrain uses a SIME-Stromag 3TWa37-TE2L single-caliper disk brake system. The brake disk is mounted with an interference fit to the end of the HSS. For the shutdown case, of primary interest are the loads reached immediately after engaging the disk brake.

Shutdown events will always be completed with the generator offline so the initial torque is essentially zero as in the field. The operation of the braking system hardware and software controls should be verified in a graduated fashion by actuating the brake calipers when the dynamometer crosses below a specified speed. Brake application speeds from 1%–11 %, in 1% increments, will be examined. Previous testing showed that similar torque responses as in the field were measured with the brake application speed reaching 11%. In this condition, the torque reaches 189% of rated.

In each condition, acquire the data specified in Table B-1 and Table B-2, initiating data acquisition just prior to brake application and continuously recording until the drivetrain stops oscillating.

5.5 Grid Disconnect Tests

Controlled shutdowns will be performed in this test sequence. While operating at a steady-state power level, the dynamometer will be intentionally shut down in a controlled fashion. The GRC generator immediately disconnects and the dynamometer ramps down at a controlled speed, taking about 3 min to come to a complete stop. Shutdowns will be performed at 25% power, 50% power, 75% power, and 100% power. It should be noted that the behavior wherein the GRC controller immediately disconnects the generator from the grid is the same behavior the controller would exhibit in response to a grid event.

6 Summary and Administrative Information

This document describes planned tests of GRC GB3 in the NWTC 2.5-MW dynamometer. Specific objectives of the test are to assess the effect of static and dynamic NTLs on the planetary section, generator misalignment on the HSS section, and field-representative conditions on the gearbox in general.

6.1 Roles and Responsibilities

Industry partners Romax Technology, Timken, and Brad Foote Gearing are responsible for design, manufacture and instrumentation of the gearbox. NREL will install the gearbox into the drivetrain, connect the instrumentation to the NREL DAS and conduct the test in accordance with this test plan. After the test, NREL will write a test report. NREL and the industry partners will jointly develop detailed analyses in subsequent publications.

6.2 Safety Compliance

The NWTC 2.5-MW dynamometer safe operating procedure specifies procedures relating to test article setup and initial commissioning test procedures [21]. A readiness verification meeting will be held prior to initiation of loaded operation.

6.3 Testing Schedule

Test article setup and interconnection will occur in May through July of 2016; initial commissioning will occur in late July. Full power testing will occur throughout the fall of 2016.

6.4 Legal Statements

The engineering details of the gearbox, with the exception of the planet-bearing geometry, are publicly available. The test data will be made publicly available along with any information required to convert the data to engineering units of interest.

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Appendix A. Drivetrain Connections

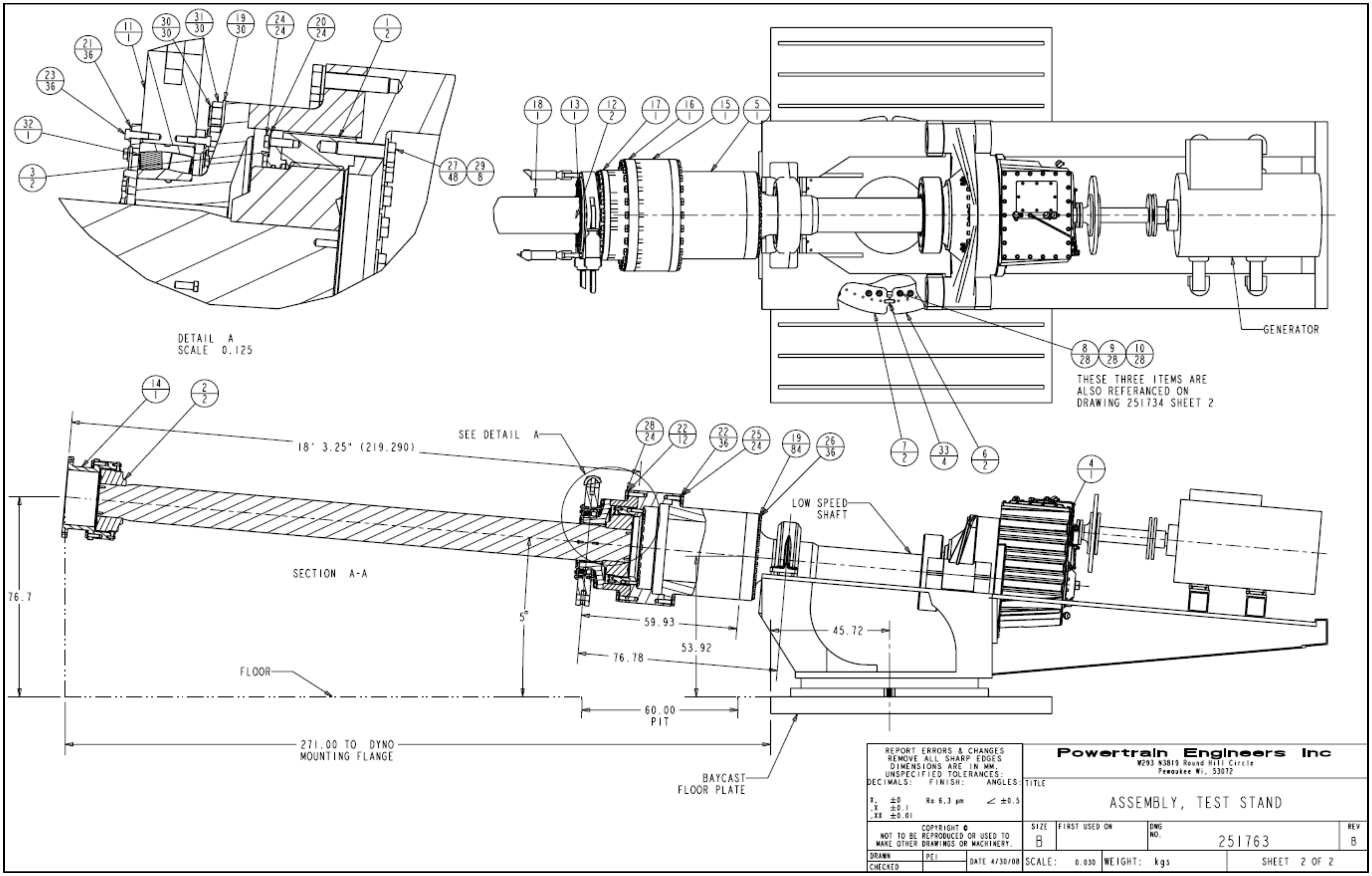


Figure A-1. Gearbox Reliability Collaborative (GRC) mechanical connection. *Illustration by Powertrain Engineers*

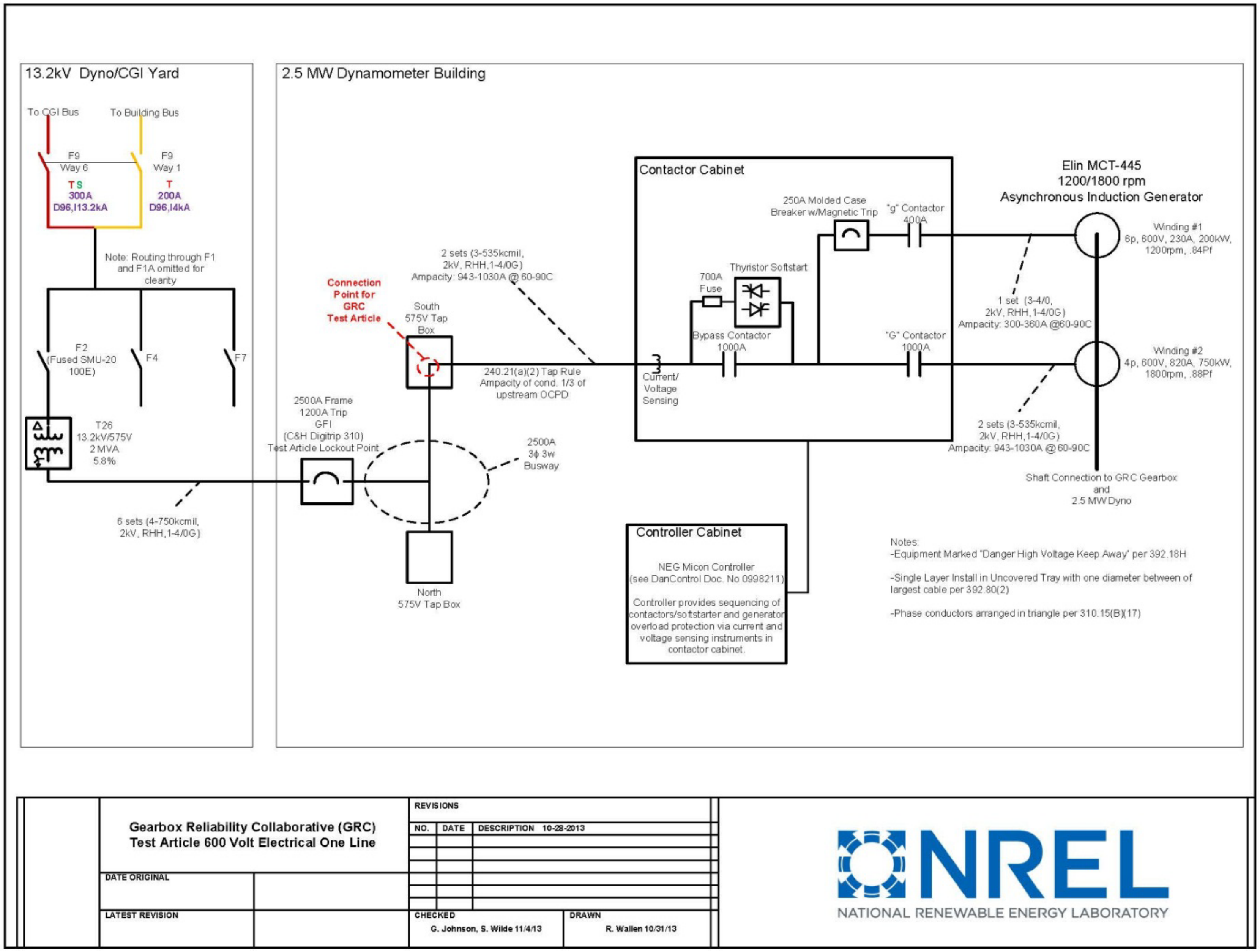


Figure A-2. GRC electrical connection

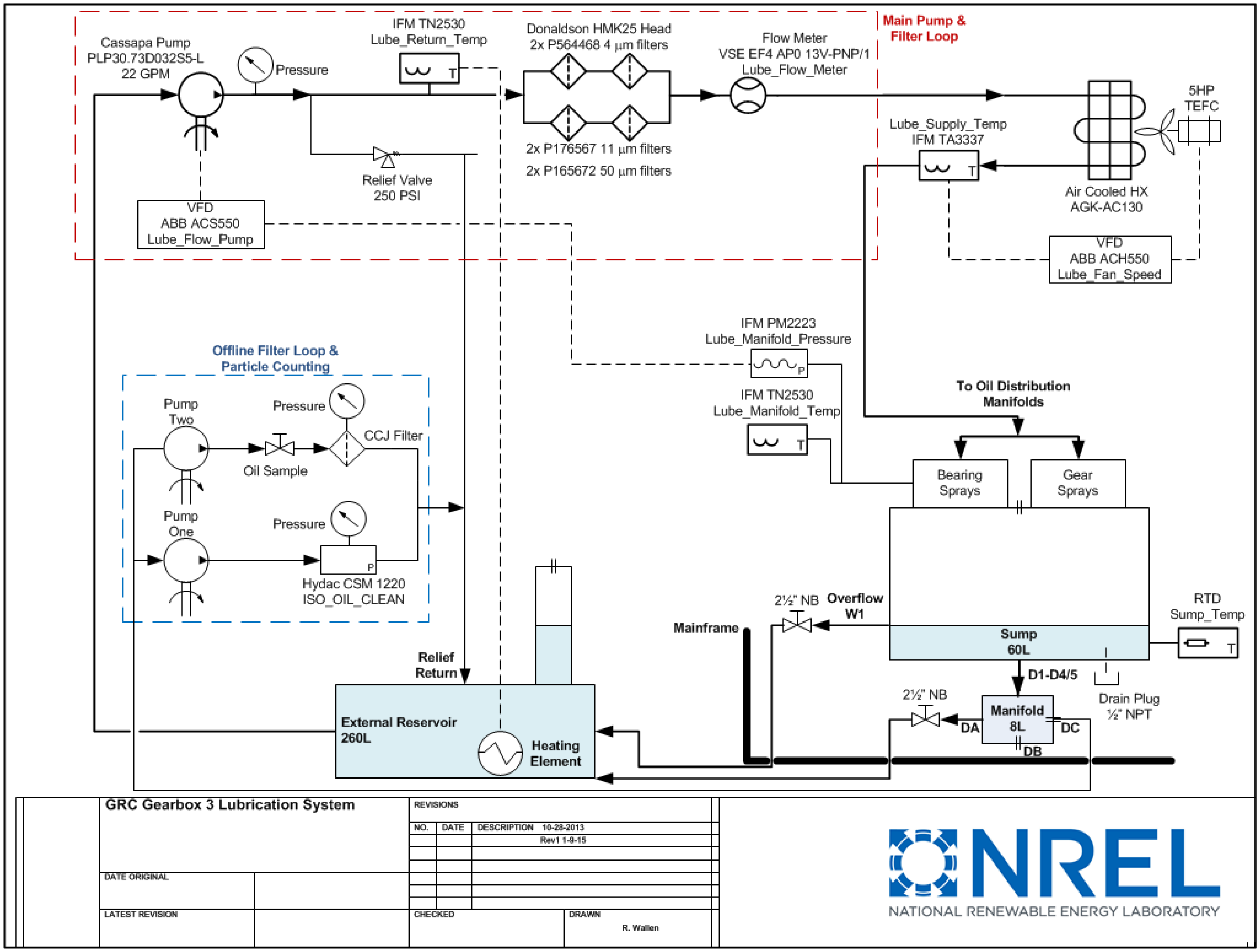


Figure A-3. GRC lubrication system connection

Appendix B. Data Elements

Table B-1. Elements of 100-Hz Sample Rate Data

Location	Nomenclature	Expanded Nomenclature	Units	Sensor(s)	Module
DAS	MS Excel Timestamp	Time, MS Excel format, from Jan 1, 1900	days	DAS	-
DAS	LabVIEW Timestamp	Time, Labview format, from Jan 1, 1904	s	DAS	-
Dyno Motor	Dyno_Speed	Speed, dynamometer gearbox output converted from dynamometer motor	rpm	Calculated	-
Dyno GB	Dyno_Torque	Torque, dynamometer gearbox output torque spool	kNm	Strain gauge	NI 9239
NTL	NTL_Port_Disp	Displacement, NTL port cylinder	mm	Proximity	
NTL	NTL_Port_Force	Force, NTL port cylinder	kN	Load cell	
NTL	NTL_Star_Disp	Displacement, NTL starboard cylinder	mm	Proximity	
NTL	NTL_Star_Force	Force, NTL starboard cylinder	kN	Load cell	
NTL	NTL_Thrust_Disp	Displacement, NTL thrust cylinder	mm	Proximity	
NTL	NTL_Thrust_Force	Force, NTL thrust cylinder	kN	Load cell	
Main shaft	LSS_TQ	Torque	kNm	Strain gauge	NI 9237
Main shaft	MSBM_YY	Bending moment, rotating, y-axis	kNm	Strain gauge	NI 9237
Main shaft	MSBM_ZZ	Bending moment, rotating, z-axis	kNm	Strain gauge	NI 9237
Main shaft	MSBM	Bending moment, total	kNm	Calculated	-
Main shaft	MSBM_yy	Bending moment, fixed, y-axis	kNm	Calculated	-
Main shaft	MSBM_zz	Bending moment, fixed, z-axis	kNm	Calculated	-
Main shaft	LSS_Azimuth	Azimuth angle	degrees	Encoder	EC-CNT4
Main shaft	LSS_Speed	Shaft speed	rpm	Calculated	-
Housing	Trunion_Z_stbd	Displacement, gearbox Z starboard	mm	Proximity	NI 9205
Housing	Trunion_Z_port	Displacement, gearbox Z port	mm	Proximity	NI 9205
Housing	Trunion_My_bottom	Displacement, gearbox X bottom	mm	Proximity	NI 9205
Housing	Trunion_Y_port	Displacement, gearbox Y port	mm	Proximity	NI 9205

Location	Nomenclature	Expanded Nomenclature	Units	Sensor(s)	Module
Housing	Trunion_X_stbd	Displacement, gearbox X starboard	mm	Proximity	NI 9205
Housing	Trunion_X_port	Displacement, gearbox X port	mm	Proximity	NI 9205
Housing	WEB_STRAIN_0	Strain in carrier web, 0° direction	mV/V	Strain gauge	NI 9236
Housing	WEB_STRAIN_45	Strain in web, 45° direction	mV/V	Strain gauge	NI 9236
Housing	WEB_STRAIN_315	Strain in web, 315° direction	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_0_A	Strain, ring gear teeth, 0° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_0_B	Strain, ring gear teeth, 0° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_0_C	Strain, ring gear teeth, 0° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_0_D	Strain, ring gear teeth, 0° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_0_E	Strain, ring gear teeth, 0° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_0_F	Strain, ring gear teeth, 0° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_0_G	Strain, ring gear teeth, 0° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_0_H	Strain, ring gear teeth, 0° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_120_A	Strain, ring gear teeth, 120° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_120_B	Strain, ring gear teeth, 120° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_120_C	Strain, ring gear teeth, 120° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_120_D	Strain, ring gear teeth, 120° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_120_E	Strain, ring gear teeth, 120° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_120_F	Strain, ring gear teeth, 120° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_120_G	Strain, ring gear teeth, 120° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_120_H	Strain, ring gear teeth, 120° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_240_A	Strain, ring gear teeth, 240° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_240_B	Strain, ring gear teeth, 240° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_240_C	Strain, ring gear teeth, 240° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_240_D	Strain, ring gear teeth, 240° location	mV/V	Strain gauge	NI 9236

Location	Nomenclature	Expanded Nomenclature	Units	Sensor(s)	Module
Ring gear	INT_KHB_240_E	Strain, ring gear teeth, 240° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_240_F	Strain, ring gear teeth, 240° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_240_G	Strain, ring gear teeth, 240° location	mV/V	Strain gauge	NI 9236
Ring gear	INT_KHB_240_H	Strain, ring gear teeth, 240° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_0_A	Strain, ring gear exterior, 0° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_0_B	Strain, ring gear exterior, 0° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_0_C	Strain, ring gear exterior, 0° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_0_D	Strain, ring gear exterior, 0° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_0_E	Strain, ring gear exterior, 0° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_0_F	Strain, ring gear exterior, 0° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_0_G	Strain, ring gear exterior, 0° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_0_H	Strain, ring gear exterior, 0° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_120_A	Strain, ring gear exterior, 120° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_120_B	Strain, ring gear exterior, 120° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_120_C	Strain, ring gear exterior, 120° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_120_D	Strain, ring gear exterior, 120° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_120_E	Strain, ring gear exterior, 120° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_120_F	Strain, ring gear exterior, 120° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_120_G	Strain, ring gear exterior, 120° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_120_H	Strain, ring gear exterior, 120° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_240_A	Strain, ring gear exterior, 240° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_240_B	Strain, ring gear exterior, 240° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_240_C	Strain, ring gear exterior, 240° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_240_D	Strain, ring gear exterior, 240° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_240_E	Strain, ring gear exterior, 240° location	mV/V	Strain gauge	NI 9236

Location	Nomenclature	Expanded Nomenclature	Units	Sensor(s)	Module
Ring gear	EXT_KHB_240_F	Strain, ring gear exterior, 240° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_240_G	Strain, ring gear exterior, 240° location	mV/V	Strain gauge	NI 9236
Ring gear	EXT_KHB_240_H	Strain, ring gear exterior, 240° location	mV/V	Strain gauge	NI 9236
Carrier	Carrier_047	Displacement, carrier, X direction, 047°	mm	Proximity	NI 9205
Carrier	Carrier_137	Displacement, carrier, X direction, 137°	mm	Proximity	NI 9205
Carrier	Carrier_227	Displacement, carrier, X direction, 227°	mm	Proximity	NI 9205
Carrier	Carrier_317	Displacement, carrier, X direction, 317°	mm	Proximity	NI 9205
Carrier	Radial_040	Displacement Radial 40°	mm	Proximity	NI 9205
Carrier	Radial_310	Displacement Radial 310°	mm	Proximity	NI 9205
Planet	PlanetB_Rim_0	Displacement, X direction, 0°	mm	Proximity	NI 9205
Planet	PlanetB_Rim_90	Displacement, X direction, 90°	mm	Proximity	NI 9205
Planet	PlanetB_Rim_180	Displacement, X direction, 180°	mm	Proximity	NI 9205
Planet	PlanetC_Rim_0	Displacement, X direction, 0°	mm	Proximity	NI 9205
Planet	PlanetC_Rim_90	Displacement, X direction, 90°	mm	Proximity	NI 9205
Planet	PlanetC_Rim_180	Displacement, X direction, 180°	mm	Proximity	NI 9205
Planet	PlanetA_LOAD_UW_70	Strain, Planet A, upwind bearing, 70°	mV/V	Strain gauge	NI 9237
Planet	PlanetA_LOAD_UW_160	Strain, Planet A, upwind bearing, 160°	mV/V	Strain gauge	NI 9237
Planet	PlanetA_LOAD_UW_250	Strain, Planet A, upwind bearing, 250°	mV/V	Strain gauge	NI 9237
Planet	PlanetA_LOAD_UW_340	Strain, Planet A, upwind bearing, 340°	mV/V	Strain gauge	NI 9237
Planet	PlanetA_LOAD_DW_20	Strain, Planet A, downwind bearing, 20°	mV/V	Strain gauge	NI 9237
Planet	PlanetA_LOAD_DW_115	Strain, Planet A, downwind bearing, 115°	mV/V	Strain gauge	NI 9237
Planet	PlanetA_LOAD_DW_200	Strain, Planet A, downwind bearing, 200°	mV/V	Strain gauge	NI 9237
Planet	PlanetA_LOAD_DW_285	Strain, Planet A, downwind bearing, 285°	mV/V	Strain gauge	NI 9237
Planet	PlanetA_TEMP_UW_OUT1	Temperature, Planet A, upwind bearing, 340°	°C	Thermocouple	NI 9211
Planet	PlanetA_TEMP_UW_IN1	Temperature, Planet A, upwind bearing, 340°	°C	Thermocouple	NI 9211

Location	Nomenclature	Expanded Nomenclature	Units	Sensor(s)	Module
Planet	PlanetA_TEMP_DW_IN1	Temperature, Planet A, downwind bearing, 20°	°C	Thermocouple	NI 9211
Planet	PlanetA_TEMP_DW_OUT1	Temperature, Planet A, downwind bearing, 20°	°C	Thermocouple	NI 9211
Planet	PlanetB_LOAD_UW_10	Strain, Planet B, upwind bearing, 10°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_UW_32	Strain, Planet B, upwind bearing, 32°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_UW_70	Strain, Planet B, upwind bearing, 70°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_UW_160	Strain, Planet B, upwind bearing, 160°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_UW_250	Strain, Planet B, upwind bearing, 250°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_UW_288	Strain, Planet B, upwind bearing, 288°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_UW_310	Strain, Planet B, upwind bearing, 310°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_UW_327.5	Strain, Planet B, upwind bearing, 327.5°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_UW_340	Strain, Planet B, upwind bearing, 340°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_UW_352.5	Strain, Planet B, upwind bearing, 352.5°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_DW_7.5	Strain, Planet B, downwind bearing, 7.5°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_DW_20	Strain, Planet B, downwind bearing, 20°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_DW_32.5	Strain, Planet B, downwind bearing, 32.5°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_DW_50	Strain, Planet B, downwind bearing, 50°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_DW_77	Strain, Planet B, downwind bearing, 77°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_DW_115	Strain, Planet B, downwind bearing, 115°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_DW_200	Strain, Planet B, downwind bearing, 200°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_DW_285	Strain, Planet B, downwind bearing, 285°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_DW_323	Strain, Planet B, downwind bearing, 323°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_LOAD_DW_350	Strain, Planet B, downwind bearing, 350°	mV/V	Strain gauge	NI 9237
Planet	PlanetB_TEMP_UW_OUT1	Temperature, Planet B, upwind bearing, 340°	°C	Thermocouple	NI 9211
Planet	PlanetB_TEMP_UW_IN1	Temperature, Planet B, upwind bearing, 340°	°C	Thermocouple	NI 9211
Planet	PlanetB_TEMP_DW_IN1	Temperature, Planet B, downwind bearing, 20°	°C	Thermocouple	NI 9211

Location	Nomenclature	Expanded Nomenclature	Units	Sensor(s)	Module
Planet	PlanetB_TEMP_DW_OUT2	Temperature, Planet B, downwind bearing, 20°	°C	Thermocouple	NI 9211
Planet	PlanetC_LOAD_UW_70	Strain, Planet C, upwind bearing, 70°	mV/V	Strain gauge	NI 9237
Planet	PlanetC_LOAD_UW_160	Strain, Planet C, upwind bearing, 160°	mV/V	Strain gauge	NI 9237
Planet	PlanetC_LOAD_UW_250	Strain, Planet C, upwind bearing, 250°	mV/V	Strain gauge	NI 9237
Planet	PlanetC_LOAD_UW_340	Strain, Planet C, upwind bearing, 340°	mV/V	Strain gauge	NI 9237
Planet	PlanetC_LOAD_DW_20	Strain, Planet C, downwind bearing, 20°	mV/V	Strain gauge	NI 9237
Planet	PlanetC_LOAD_DW_115	Strain, Planet C, downwind bearing, 115°	mV/V	Strain gauge	NI 9237
Planet	PlanetC_LOAD_DW_200	Strain, Planet C, downwind bearing, 200°	mV/V	Strain gauge	NI 9237
Planet	PlanetC_LOAD_DW_285	Strain, Planet C, downwind bearing, 285°	mV/V	Strain gauge	NI 9237
Planet	PlanetC_TEMP_UW_OUT1	Temperature, Planet C, upwind bearing, 340°	°C	Thermocouple	NI 9211
Planet	PlanetC_TEMP_UW_IN1	Temperature, Planet C, upwind bearing, 340°	°C	Thermocouple	NI 9211
Planet	PlanetC_TEMP_DW_IN1	Temperature, Planet C, downwind bearing, 20°	°C	Thermocouple	NI 9211
Planet	PlanetC_TEMP_DW_OUT1	Temperature, Planet C, downwind bearing, 20°	°C	Thermocouple	NI 9211
Sun	Sun_radial_ZZ	Displacement, radial, Z direction	mm	Proximity	NI 9205
Sun	Sun_radial_YY	Displacement, radial, Y direction	mm	Proximity	NI 9205
LSS	Temp_LSS_DW_BRG	Temperature, outer race	°C	RTD	NI 9217
ISS	Temp_ISS_DW_BRG	Temperature, outer race	°C	RTD	NI 9217
HSS	HSS_Speed	Shaft speed	rpm	Calculated	-
HSS	HSS_Azimuth	Azimuth angle	degrees	Encoder	EC-CNT4
HSS	HSS_TQ	Torque	mV/V	Strain gauge	NI 9237
HSS	TEMP_HSS_TRB_IR_UW	Temperature, upwind TRB inner ring	°C	RTD	NI 9217
HSS	TEMP_HSS_TRB_IR_DW	Temperature, downwind TRB inner ring	°C	RTD	NI 9217
HSS	TEMP_HSS_TRB_OR_UW	Temperature, upwind TRB outer ring	°C	RTD	NI 9217
HSS	TEMP_HSS_TRB_OR_DW	Temperature, downwind TRB outer ring	°C	RTD	NI 9217
Lube System	ISO_OIL_CLEAN	Oil cleanliness, raw signal	-	CSM 1220	NI 9239

Location	Nomenclature	Expanded Nomenclature	Units	Sensor(s)	Module
Lube System	ISO_1	Oil cleanliness, bin 1	-	Calculated	-
Lube System	ISO_2	Oil cleanliness, bin 2	-	Calculated	-
Lube System	ISO_3	Oil cleanliness, bin 3	-	Calculated	-
Lube System	Lube_Flow_Pump	Flow rate, total, at lube pump	lpm	Fan speed	Calculated
Lube System	Lube_Return_Temp	Temperature, oil at main pump	°C	RTD	
Lube System	Lube_Flow_Meter	Flow rate, to gearbox, at lube pump	lpm	Flow meter	
Lube System	Lube_Fan_Speed	Speed, lube system fan	rpm	Fan speed	
Lube System	Lube_Manifold_Pressure	Pressure, oil at distribution manifold	psi	Pressure	
Lube System	Lube_Manifold_Temp	Temperature, oil at distribution manifold	°C	RTD	
Lube System	Sump_Temp	Temperature, oil in gearbox sump	°C	RTD	NI 9217
Controller	Controller_G_contactor	Large-generator contactor	-	Relay	NI 9205
Controller	Controller_g_contactor	Small-generator contactor	-	Relay	NI 9205
Controller	Controller_bypass_contactor	Soft-start bypass contactor	-	Relay	NI 9205
Controller	kW	Power, real	kW	Transformer	NI 9229
Controller	kVAR	Power, reactive	kVAR	Transformer	NI 9229

Table B-2. Elements of 2,000-Hz Sample Rate Data

Location	Nomenclature	Expanded Nomenclature	Units	Sensor(s)	Module
DAS	MS Excel Timestamp	Time, MS Excel format, from Jan 1, 1900	days	DAS	-
DAS	LabVIEW Timestamp	Time, Labview format, from Jan 1, 1904	s	DAS	-
Dyno Motor	Dyno_Speed	Speed, dynamometer gearbox output converted from dynamometer motor	rpm	Calculated	-
Dyno GB	Dyno_Torque	Torque, dynamometer gearbox output torque spool	kNm	Strain gauge	NI 9239
Main shaft	LSS_TQ	Torque	kNm	Strain gauge	NI 9237
Main shaft	MSBM_YY	Bending moment, rotating, y-axis	kNm	Strain gauge	NI 9237
Main shaft	MSBM_ZZ	Bending moment, rotating, z-axis	kNm	Strain gauge	NI 9237
Main shaft	MSBM	Bending moment, total	kNm	Calculated	-
Main shaft	MSBM_yy	Bending moment, fixed, y-axis	kNm	Calculated	-
Main shaft	MSBM_zz	Bending moment, fixed, z-axis	kNm	Calculated	-
Main shaft	LSS_Azimuth	Azimuth angle	degrees	Encoder	EC-CNT4
Main shaft	LSS_Speed	Shaft speed	rpm	Calculated	-
HSS	HSS_UY_BM	Bending moment, upwind of mesh, rotating, y-axis	mV/V	Strain gauge	NI 9237
HSS	HSS_UZ_BM	Bending moment, upwind of mesh, rotating, z-axis	mV/V	Strain gauge	NI 9237
HSS	HSS_DY_BM	Bending moment, downwind of mesh, rotating, y-axis	mV/V	Strain gauge	NI 9237
HSS	HSS_DZ_BM	Bending moment, downwind of mesh, rotating, z-axis	mV/V	Strain gauge	NI 9237
HSS	HSS_exY_BM	Bending moment, downwind of bearings, rotating, y-axis	mV/V	Strain gauge	NI 9237
HSS	HSS_exZ_BM	Bending moment, downwind of bearings, rotating, z-axis	mV/V	Strain gauge	NI 9237
HSS	HSS_TQ	Torque	mV/V	Strain gauge	NI 9237
HSS	TEMP_HSS_TRB_IR_UW	Temperature, upwind TRB inner ring	°C	RTD	NI 9217
HSS	TEMP_HSS_TRB_IR_DW	Temperature, downwind TRB inner ring	°C	RTD	NI 9217
HSS	TEMP_HSS_TRB_OR_UW	Temperature, upwind TRB outer ring	°C	RTD	NI 9217
HSS	TEMP_HSS_TRB_OR_DW	Temperature, downwind TRB outer ring	°C	RTD	NI 9217

Location	Nomenclature	Expanded Nomenclature	Units	Sensor(s)	Module
HSS	HSS_Speed	Shaft speed	rpm	Calculated	-
HSS	HSS_Azimuth	Azimuth angle	degrees	Encoder	EC-CNT4
Controller	Controller_G_contactor	Large-generator contactor	-	Relay	NI 9205
Controller	Controller_g_contactor	Small-generator contactor	-	Relay	NI 9205
Controller	Controller_bypass_contactor	Soft-start bypass contactor	-	Relay	NI 9205
Controller	kW	Power, real	kW	Transformer	NI 9229
Controller	kVAR	Power, reactive	kVAR	Transformer	NI 9229

Appendix C. Instrumentation Details

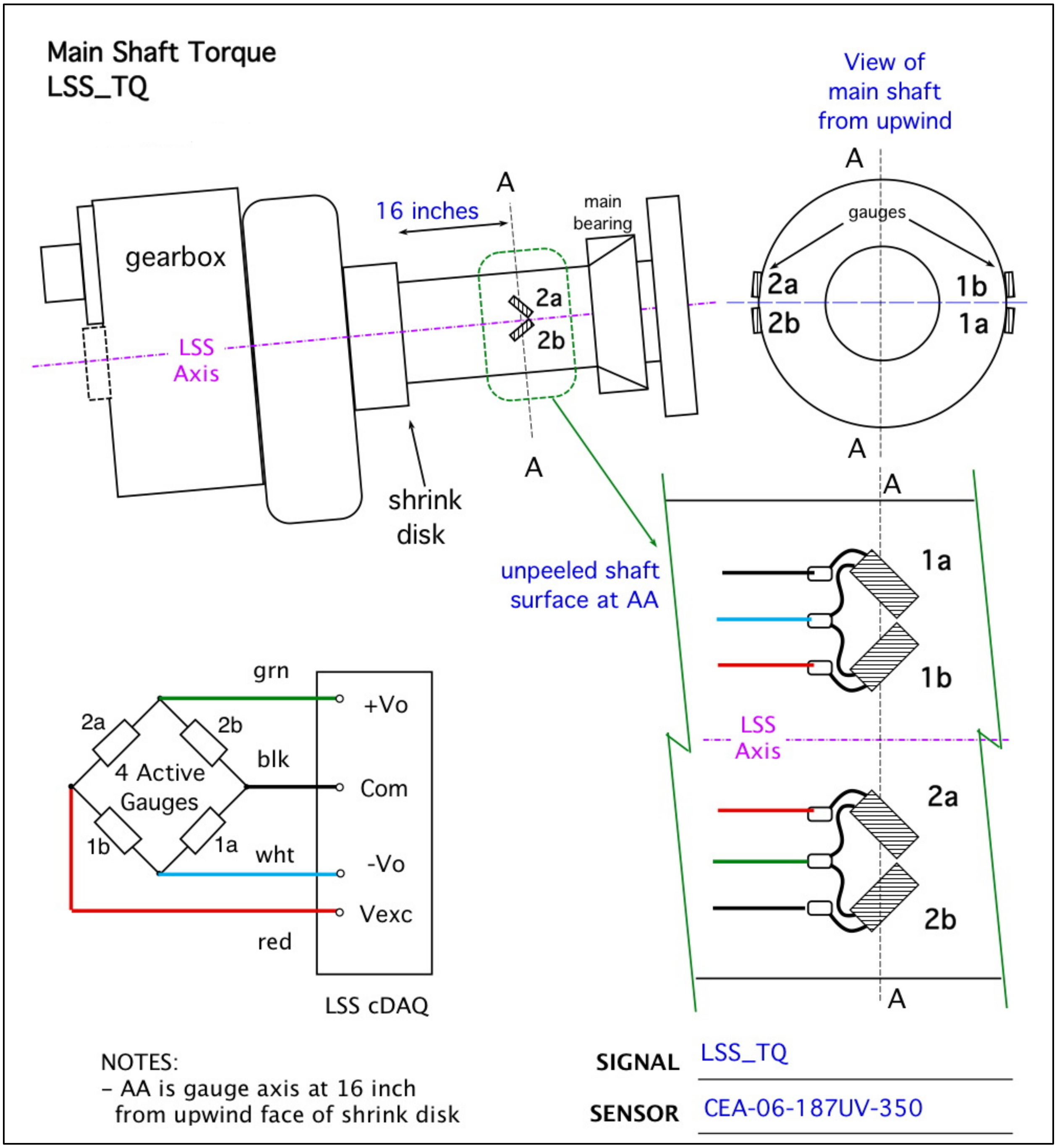


Figure C-1. Main shaft torque. *Illustration by McNiff Light Industry*

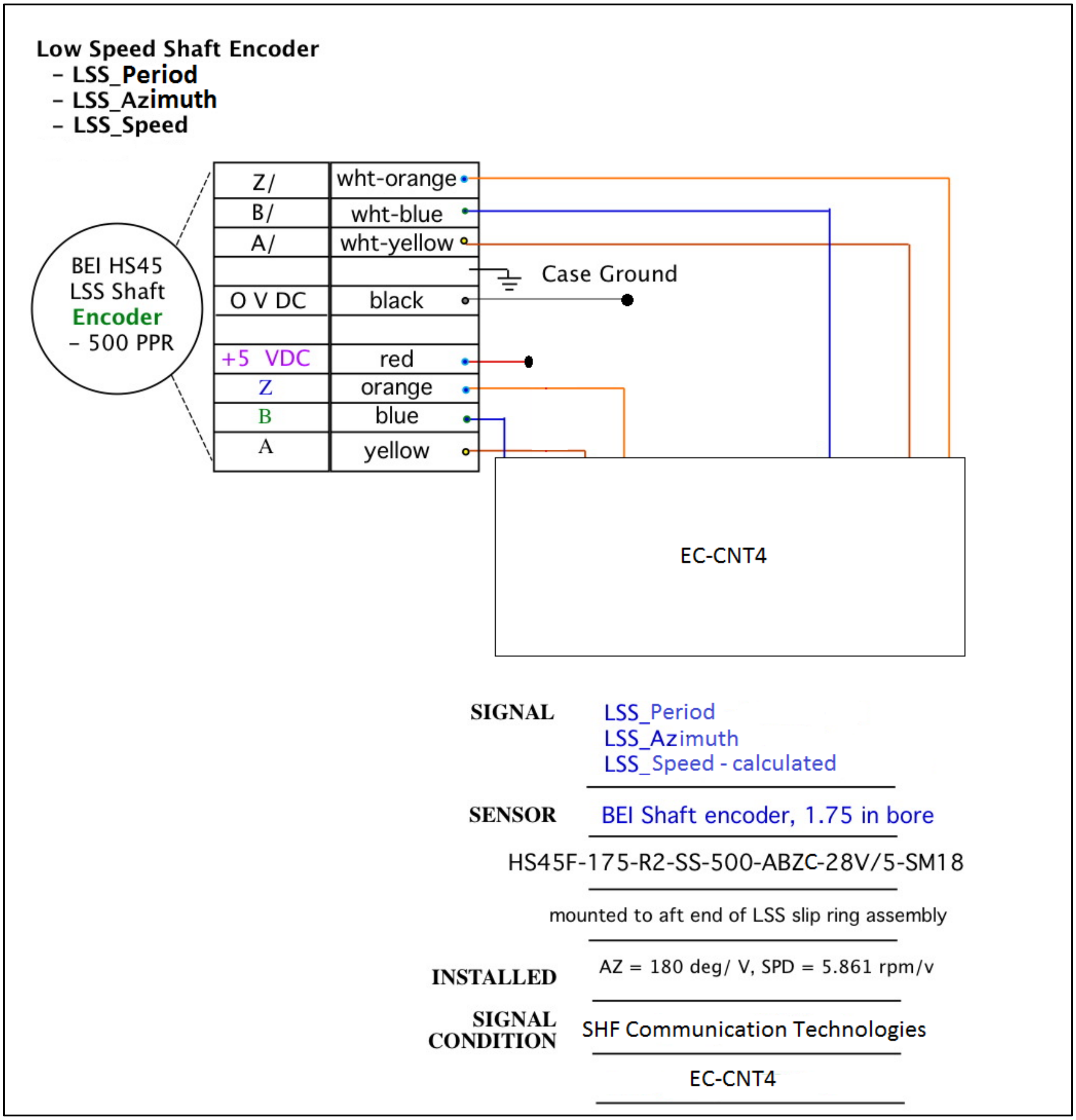


Figure C-2. Main shaft speed and azimuth. *Illustration by McNiff Light Industry*

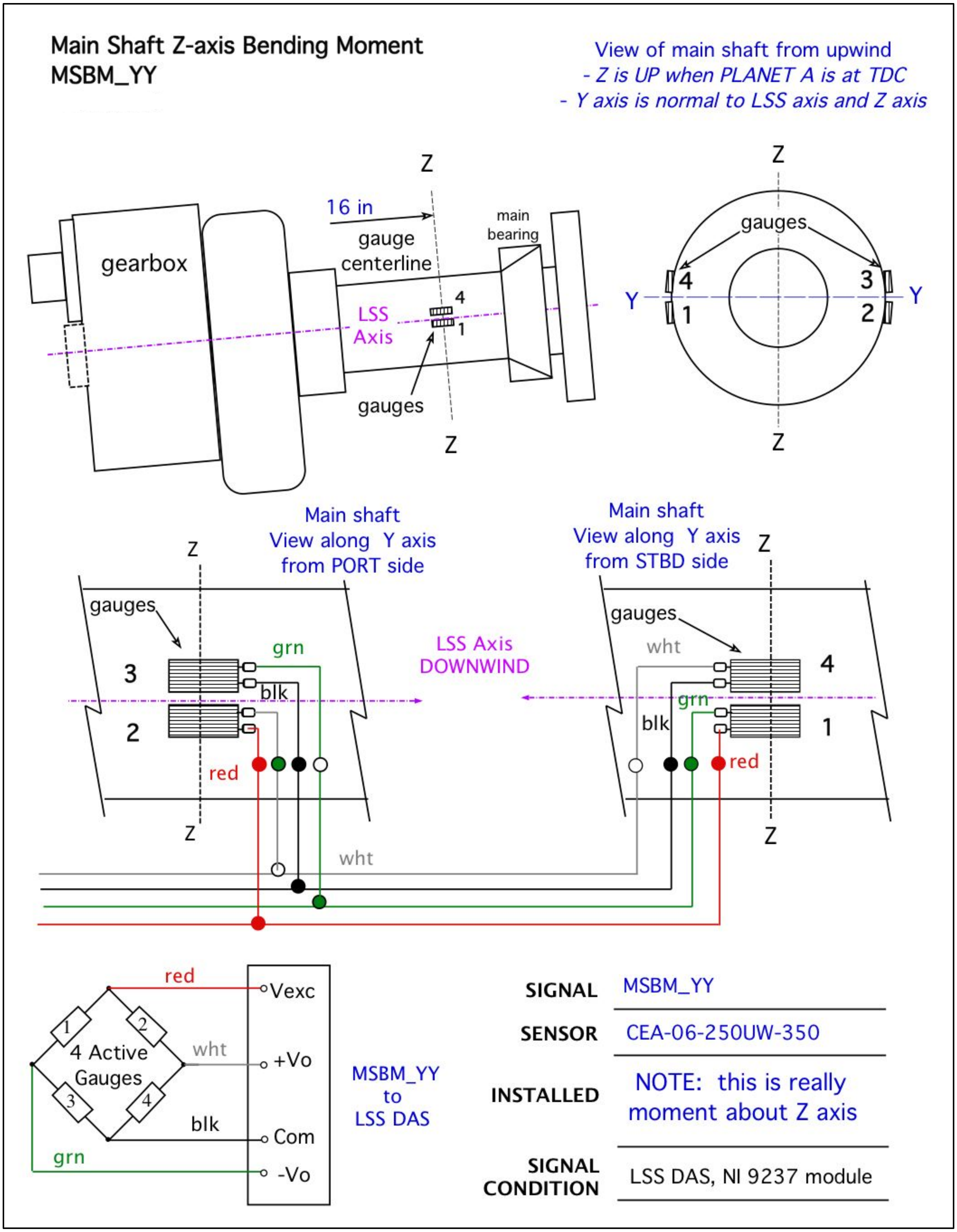


Figure C-3. Main shaft z-axis bending moment. *Illustration by McNiff Light Industry*

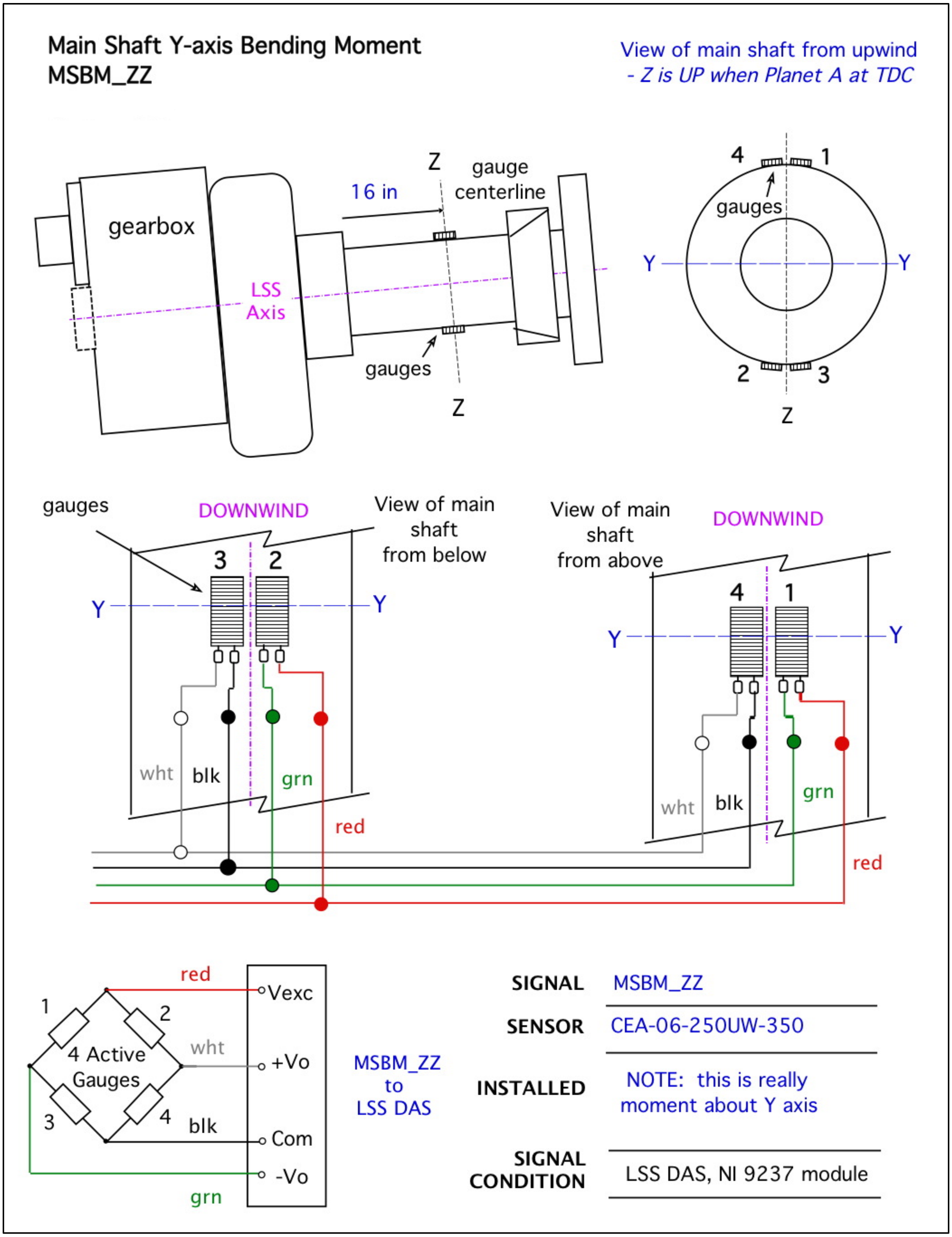
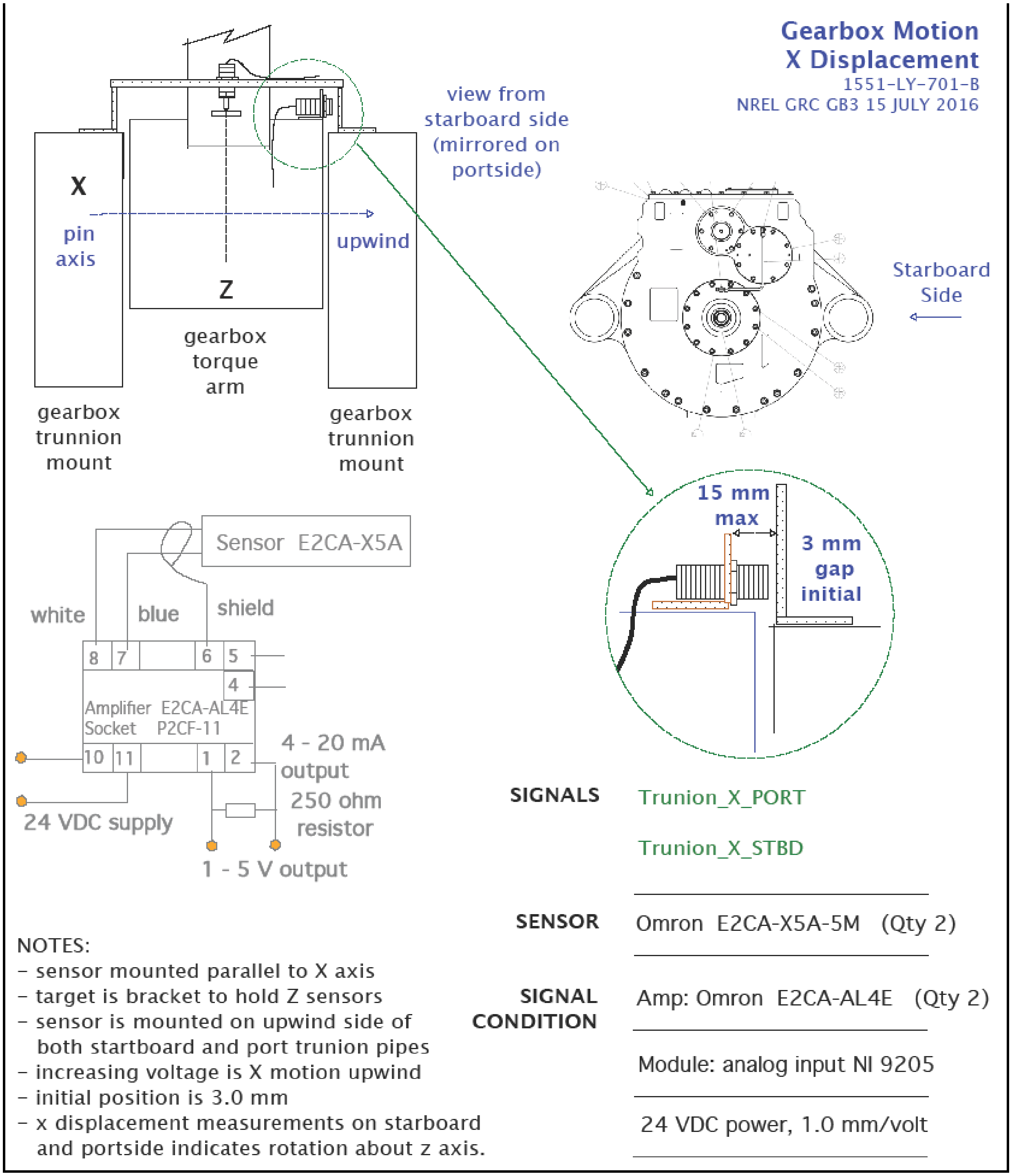


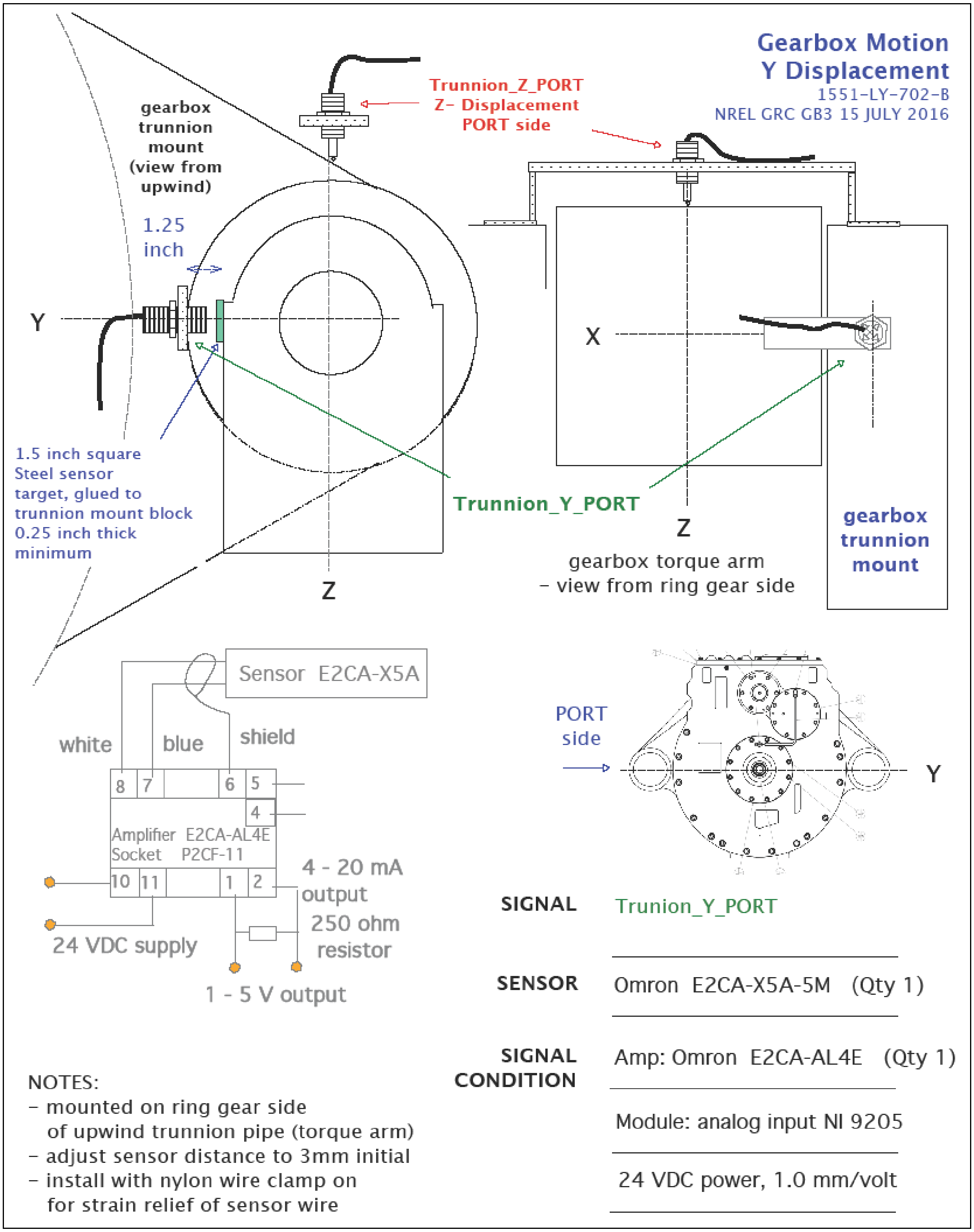
Figure C-4. Main shaft y-axis bending moment. *Illustration by McNiff Light Industry*



NOTES:
- sensor mounted parallel to X axis
- target is bracket to hold Z sensors
- sensor is mounted on upwind side of both startboard and port trunion pipes
- increasing voltage is X motion upwind
- initial position is 3.0 mm
- x displacement measurements on starboard and portside indicates rotation about z axis.

SIGNALS	Trunion_X_PORT Trunion_X_STBD
SENSOR	Omron E2CA-X5A-5M (Qty 2)
SIGNAL CONDITION	Amp: Omron E2CA-AL4E (Qty 2)
	Module: analog input NI 9205
	24 VDC power, 1.0 mm/volt

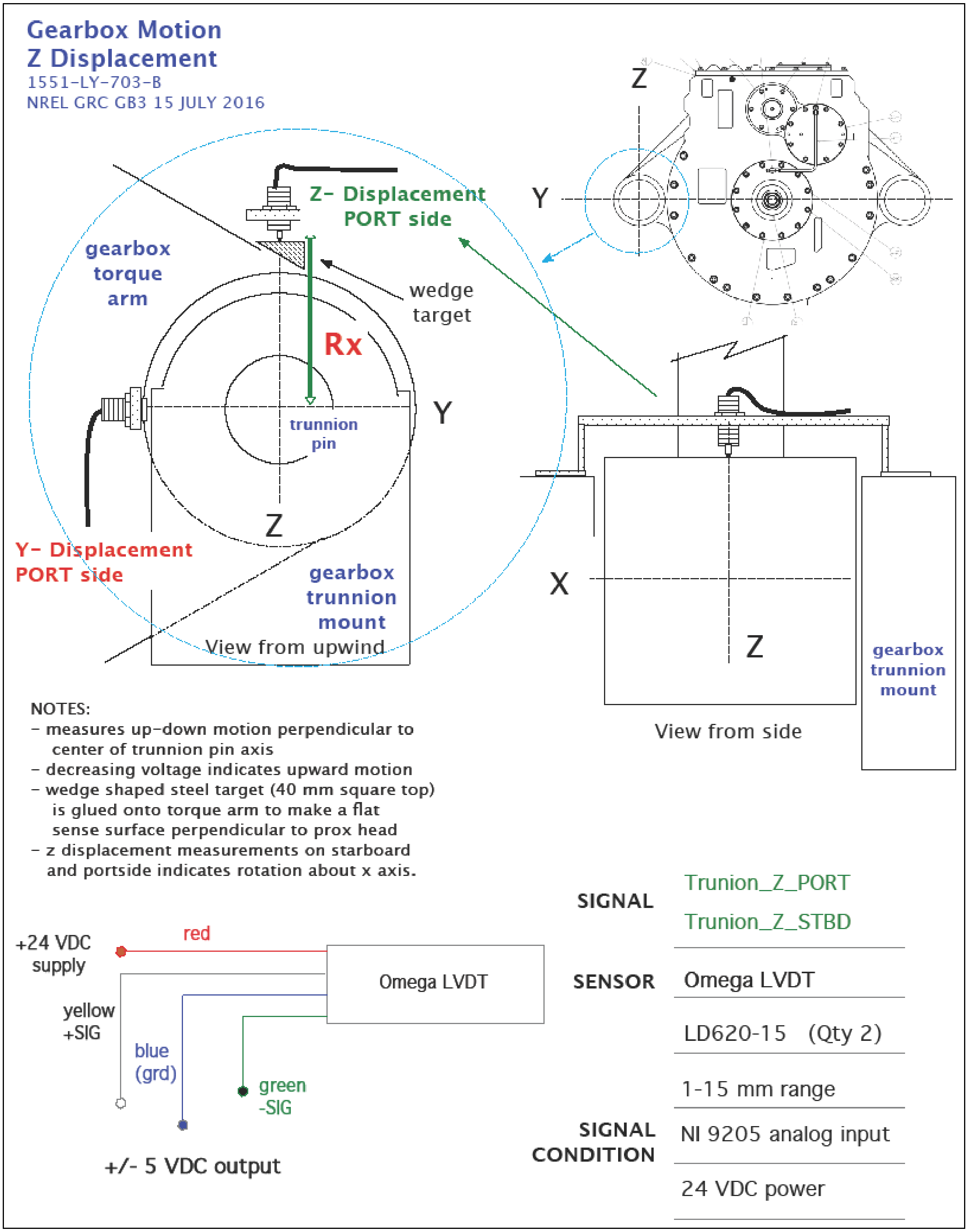
Figure C-5. Gearbox axial motion. *Illustration by Romax Technology*



SIGNAL	Trunion_Y_PORT
SENSOR	Omron E2CA-X5A-5M (Qty 1)
SIGNAL CONDITION	Amp: Omron E2CA-AL4E (Qty 1)
	Module: analog input NI 9205
	24 VDC power, 1.0 mm/volt

NOTES:
- mounted on ring gear side
  of upwind trunnion pipe (torque arm)
- adjust sensor distance to 3mm initial
- install with nylon wire clamp on
  for strain relief of sensor wire

Figure C-6. Gearbox lateral motion. *Illustration by Romax Technology*

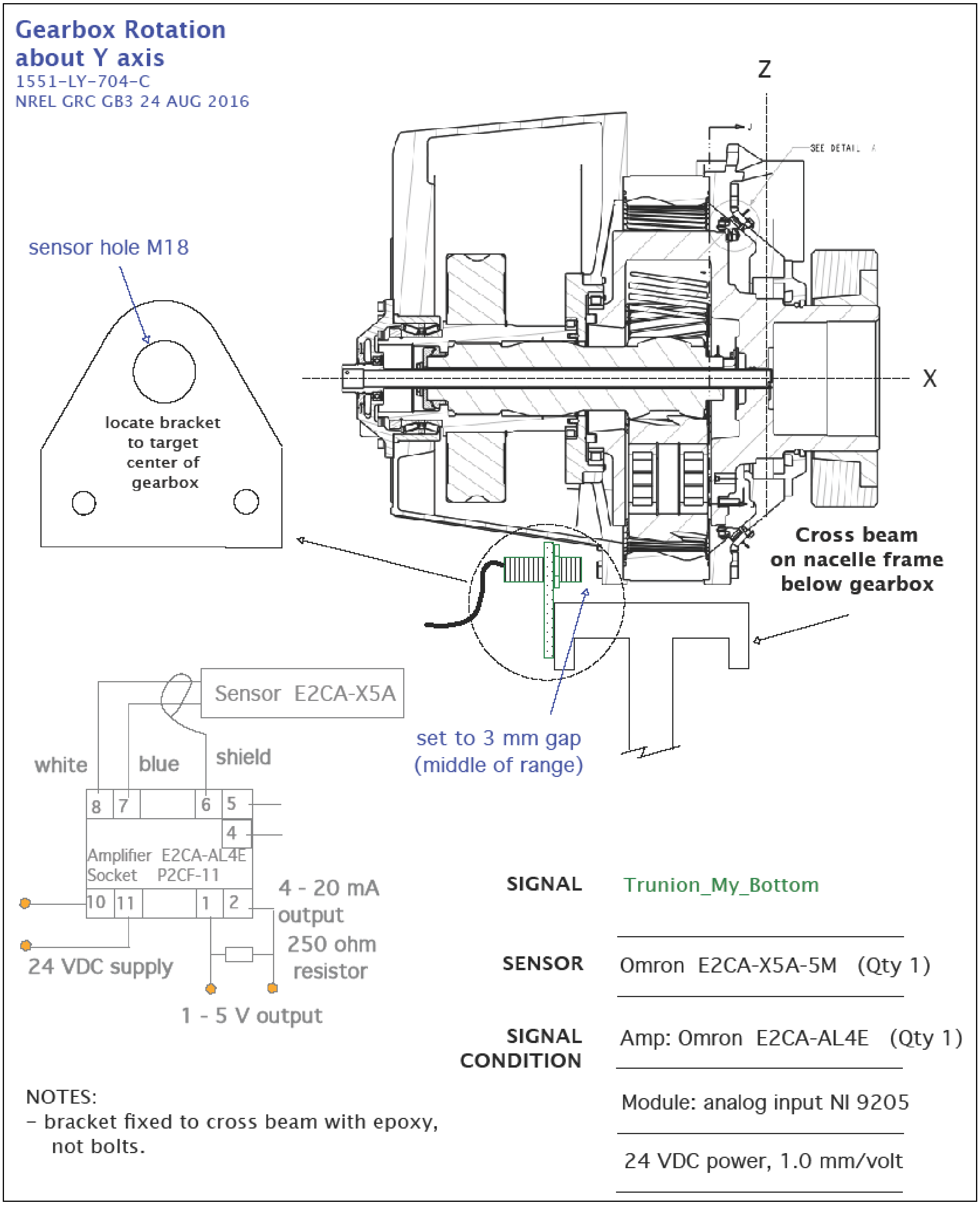


NOTES:

- measures up-down motion perpendicular to center of trunnion pin axis
- decreasing voltage indicates upward motion
- wedge shaped steel target (40 mm square top) is glued onto torque arm to make a flat sense surface perpendicular to prox head
- z displacement measurements on starboard and portside indicates rotation about x axis.

SIGNAL	Trunion_Z_PORT Trunion_Z_STBD
SENSOR	Omega LVDT
	LD620-15 (Qty 2)
	1-15 mm range
SIGNAL CONDITION	NI 9205 analog input
	24 VDC power

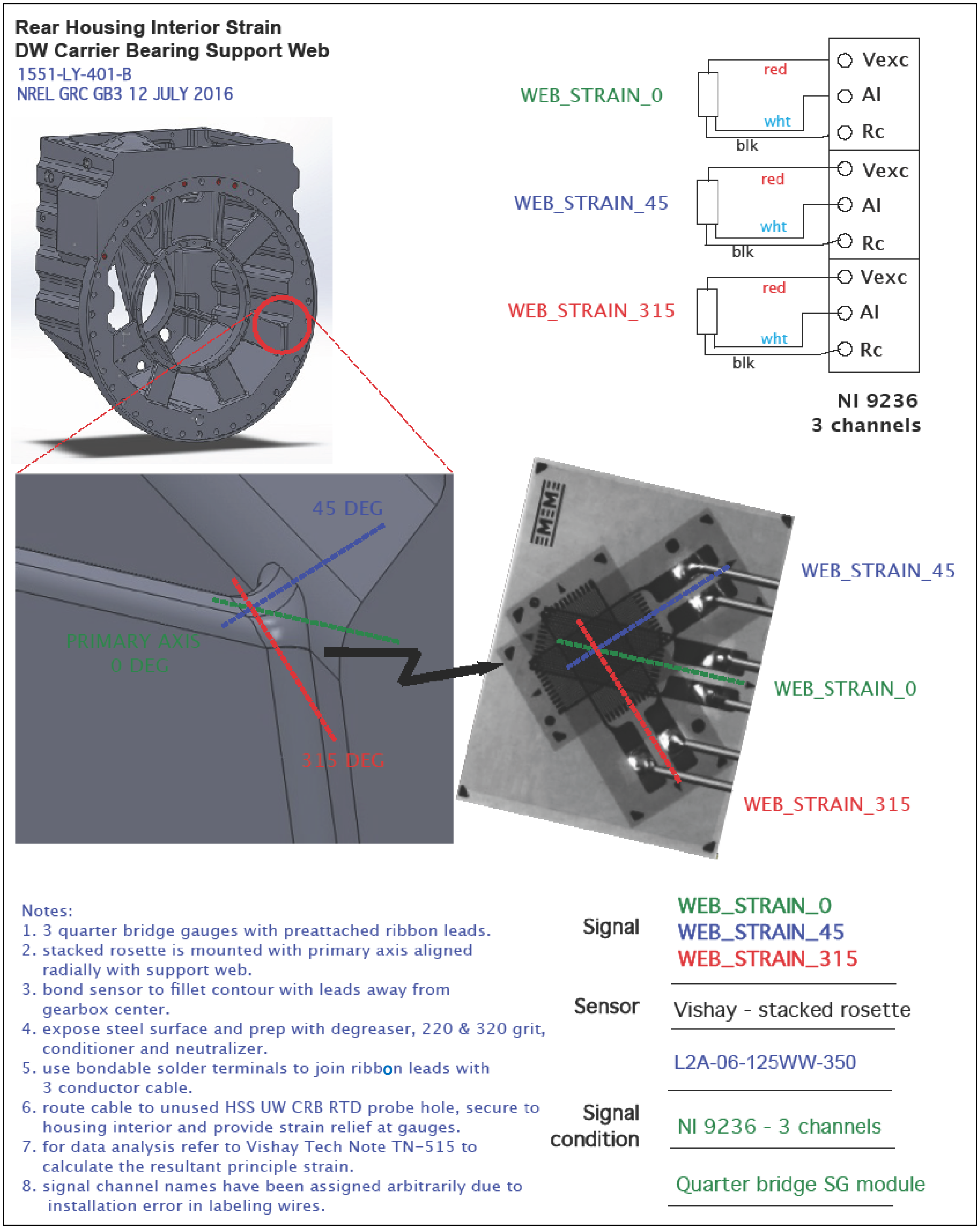
Figure C-7. Gearbox vertical motion. *Illustration by Romax Technology*



SIGNAL	Trunion_My_Bottom
SENSOR	Omron E2CA-X5A-5M (Qty 1)
SIGNAL CONDITION	Amp: Omron E2CA-AL4E (Qty 1)
	Module: analog input NI 9205
	24 VDC power, 1.0 mm/volt

NOTES:
- bracket fixed to cross beam with epoxy, not bolts.

Figure C-8. Gearbox pitch motion. *Illustration by Romax Technology*

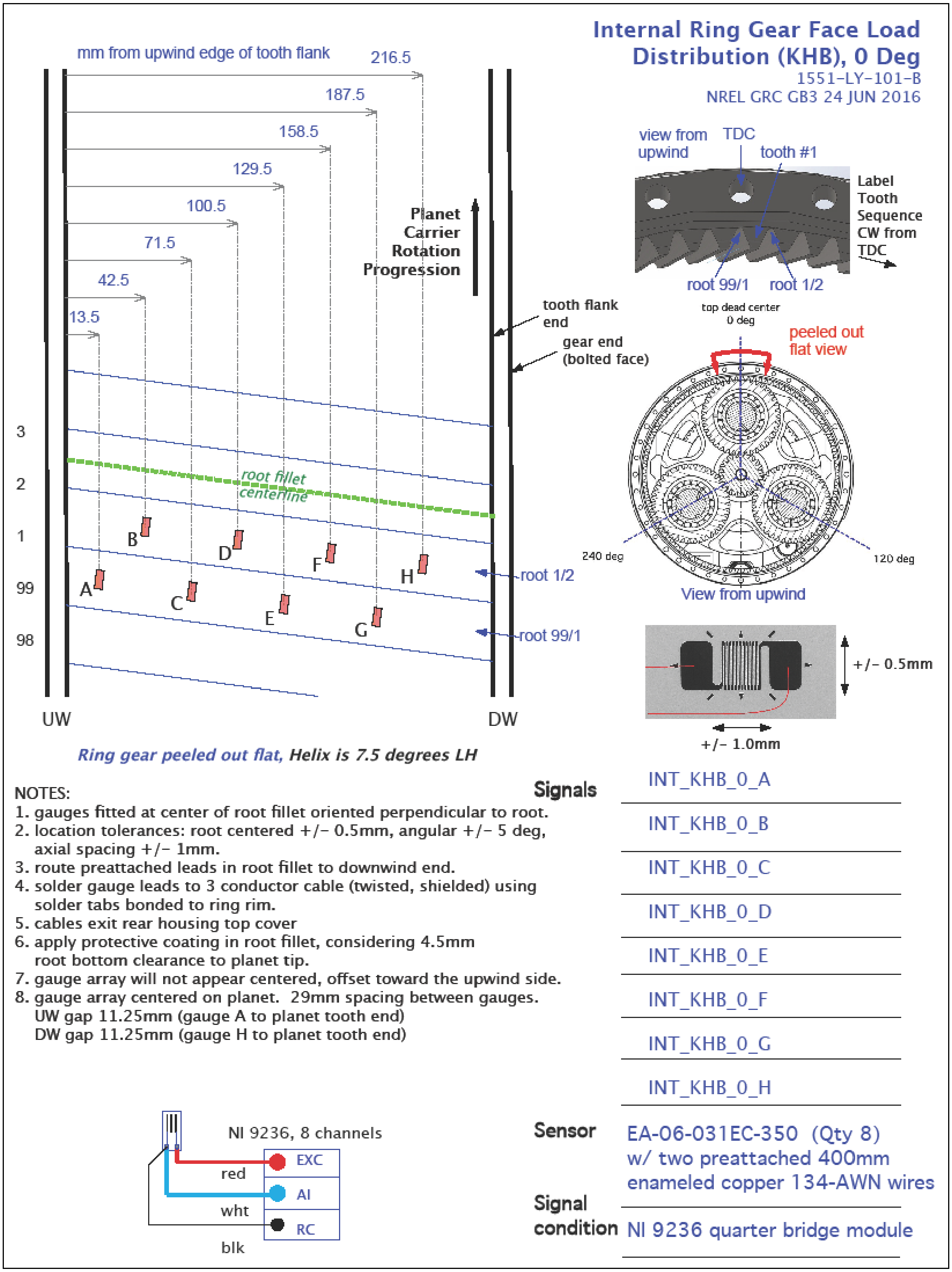


Notes:

1. 3 quarter bridge gauges with preattached ribbon leads.
2. stacked rosette is mounted with primary axis aligned radially with support web.
3. bond sensor to fillet contour with leads away from gearbox center.
4. expose steel surface and prep with degreaser, 220 & 320 grit, conditioner and neutralizer.
5. use bondable solder terminals to join ribbon leads with 3 conductor cable.
6. route cable to unused HSS UW CRB RTD probe hole, secure to housing interior and provide strain relief at gauges.
7. for data analysis refer to Vishay Tech Note TN-515 to calculate the resultant principle strain.
8. signal channel names have been assigned arbitrarily due to installation error in labeling wires.

Signal	WEB_STRAIN_0 WEB_STRAIN_45 WEB_STRAIN_315
Sensor	Vishay - stacked rosette L2A-06-125WW-350
Signal condition	NI 9236 - 3 channels Quarter bridge SG module

Figure C-9. Housing web strain. *Illustration by Romax Technology*



NOTES:
1. gauges fitted at center of root fillet oriented perpendicular to root.
2. location tolerances: root centered +/- 0.5mm, angular +/- 5 deg, axial spacing +/- 1mm.
3. route preattached leads in root fillet to downwind end.
4. solder gauge leads to 3 conductor cable (twisted, shielded) using solder tabs bonded to ring rim.
5. cables exit rear housing top cover
6. apply protective coating in root fillet, considering 4.5mm root bottom clearance to planet tip.
7. gauge array will not appear centered, offset toward the upwind side.
8. gauge array centered on planet. 29mm spacing between gauges.
   UW gap 11.25mm (gauge A to planet tooth end)
   DW gap 11.25mm (gauge H to planet tooth end)

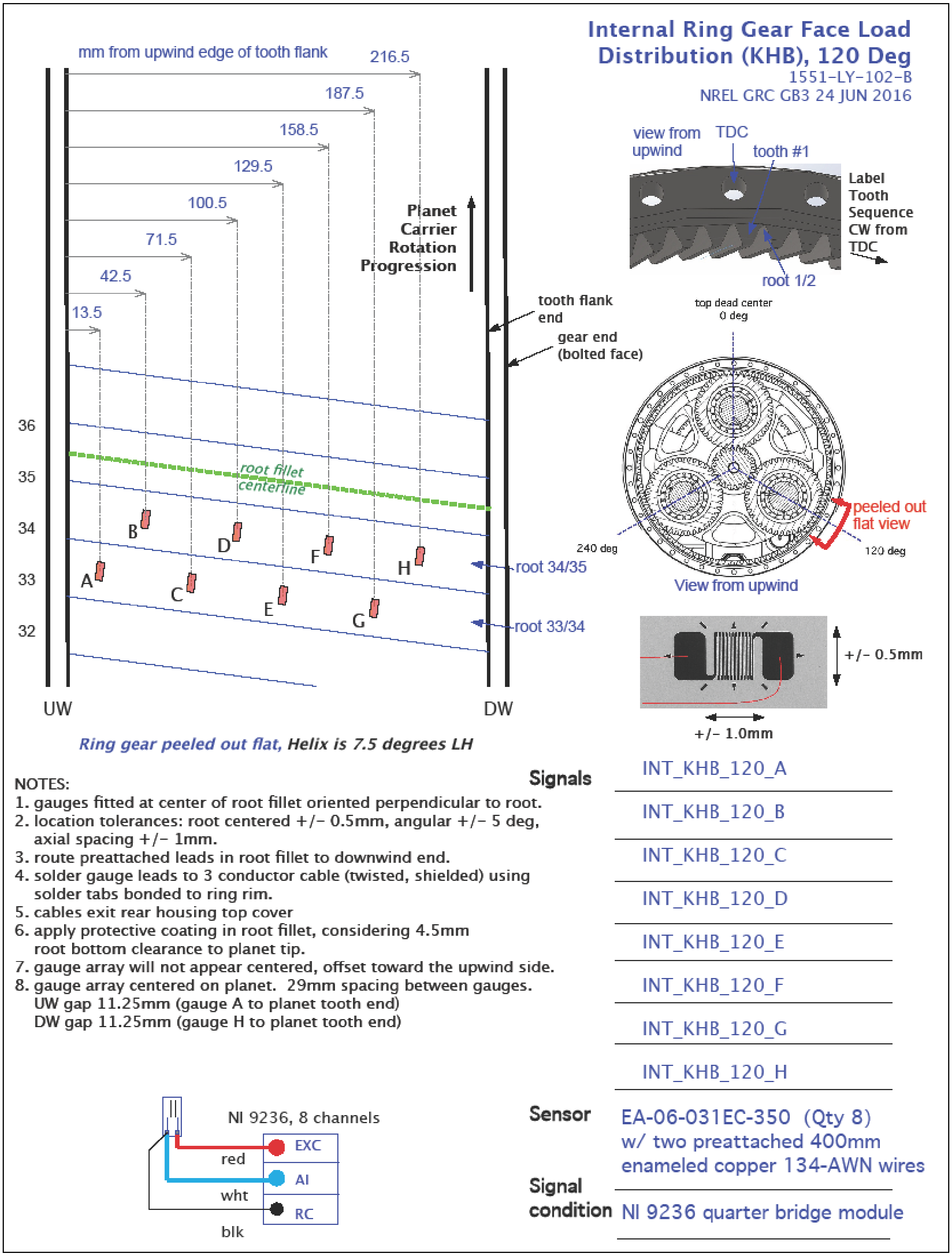
Signals

INT_KHB_0_A
INT_KHB_0_B
INT_KHB_0_C
INT_KHB_0_D
INT_KHB_0_E
INT_KHB_0_F
INT_KHB_0_G
INT_KHB_0_H

Sensor EA-06-031EC-350 (Qty 8) w/ two preattached 400mm enameled copper 134-AWN wires

Signal condition NI 9236 quarter bridge module

Figure C-10. Internal ring gear 0° face width load distribution. *Illustration by Romax Technology*



Internal Ring Gear Face Load Distribution (KHB), 120 Deg
1551-LY-102-B
NREL GRC GB3 24 JUN 2016

Ring gear peeled out flat, **Helix is 7.5 degrees LH**

NOTES:
1. gauges fitted at center of root fillet oriented perpendicular to root.
2. location tolerances: root centered +/- 0.5mm, angular +/- 5 deg, axial spacing +/- 1mm.
3. route preattached leads in root fillet to downwind end.
4. solder gauge leads to 3 conductor cable (twisted, shielded) using solder tabs bonded to ring rim.
5. cables exit rear housing top cover
6. apply protective coating in root fillet, considering 4.5mm root bottom clearance to planet tip.
7. gauge array will not appear centered, offset toward the upwind side.
8. gauge array centered on planet. 29mm spacing between gauges.
   UW gap 11.25mm (gauge A to planet tooth end)
   DW gap 11.25mm (gauge H to planet tooth end)

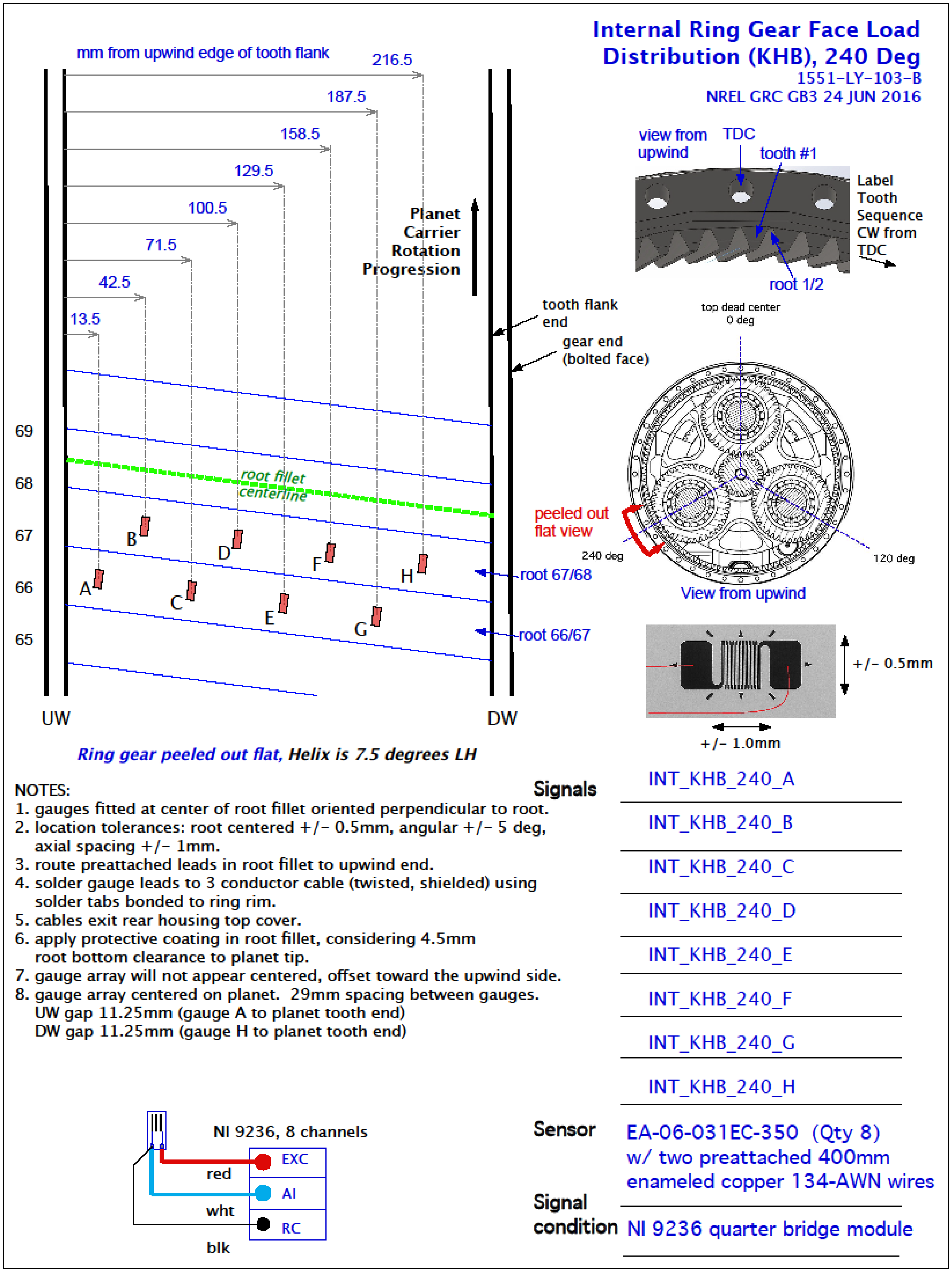
Signals

INT_KHB_120_A
INT_KHB_120_B
INT_KHB_120_C
INT_KHB_120_D
INT_KHB_120_E
INT_KHB_120_F
INT_KHB_120_G
INT_KHB_120_H

Sensor EA-06-031EC-350 (Qty 8) w/ two preattached 400mm enameled copper 134-AWN wires

Signal condition NI 9236 quarter bridge module

Figure C-11. Internal ring gear 120° face width load distribution. *Illustration by Romax Technology*



NOTES:
1. gauges fitted at center of root fillet oriented perpendicular to root.
2. location tolerances: root centered +/- 0.5mm, angular +/- 5 deg, axial spacing +/- 1mm.
3. route preattached leads in root fillet to upwind end.
4. solder gauge leads to 3 conductor cable (twisted, shielded) using solder tabs bonded to ring rim.
5. cables exit rear housing top cover.
6. apply protective coating in root fillet, considering 4.5mm root bottom clearance to planet tip.
7. gauge array will not appear centered, offset toward the upwind side.
8. gauge array centered on planet. 29mm spacing between gauges.
   UW gap 11.25mm (gauge A to planet tooth end)
   DW gap 11.25mm (gauge H to planet tooth end)

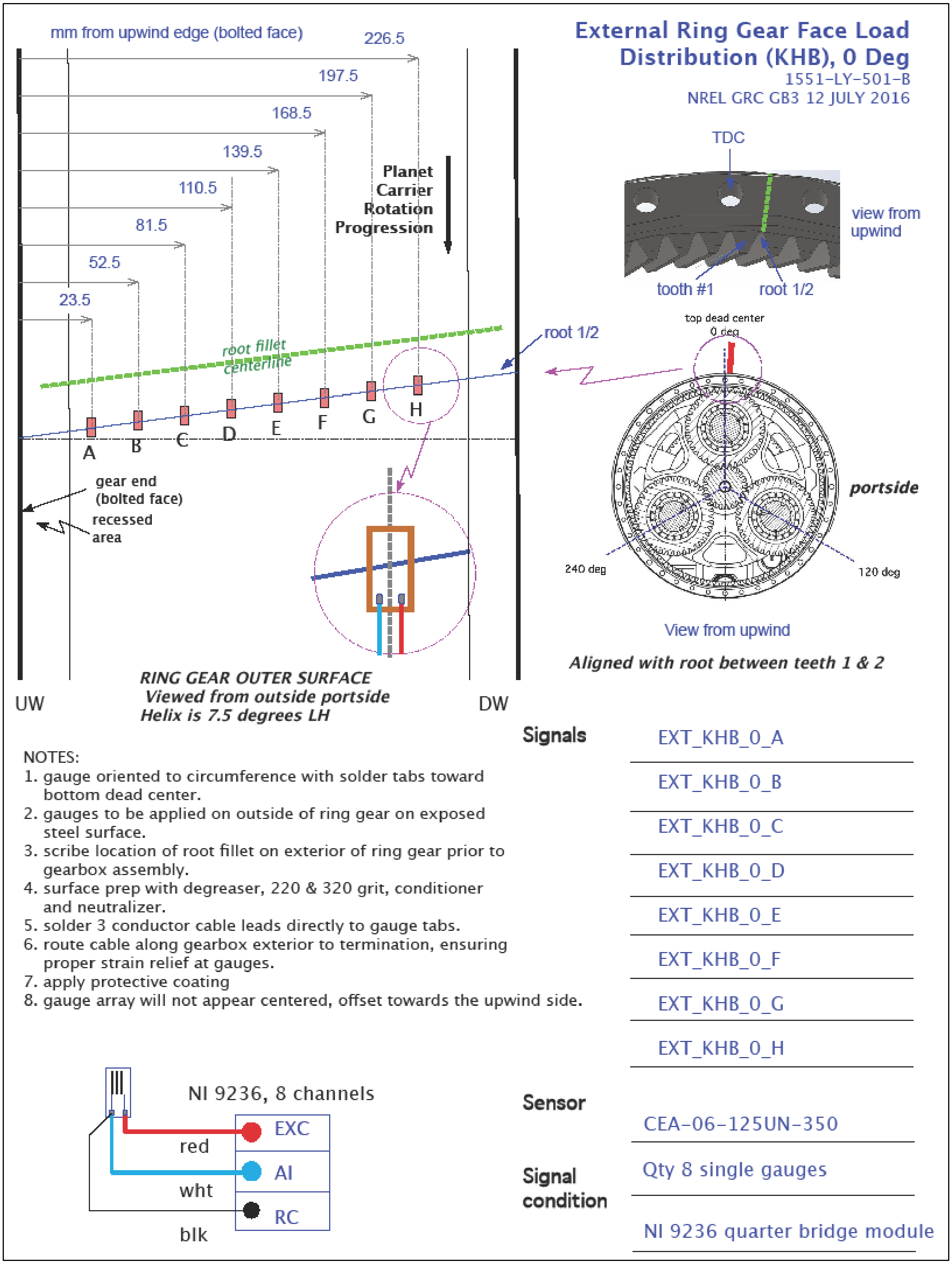
Signals

INT_KHB_240_A
INT_KHB_240_B
INT_KHB_240_C
INT_KHB_240_D
INT_KHB_240_E
INT_KHB_240_F
INT_KHB_240_G
INT_KHB_240_H

Sensor EA-06-031EC-350 (Qty 8) w/ two preattached 400mm enameled copper 134-AWN wires

Signal condition NI 9236 quarter bridge module

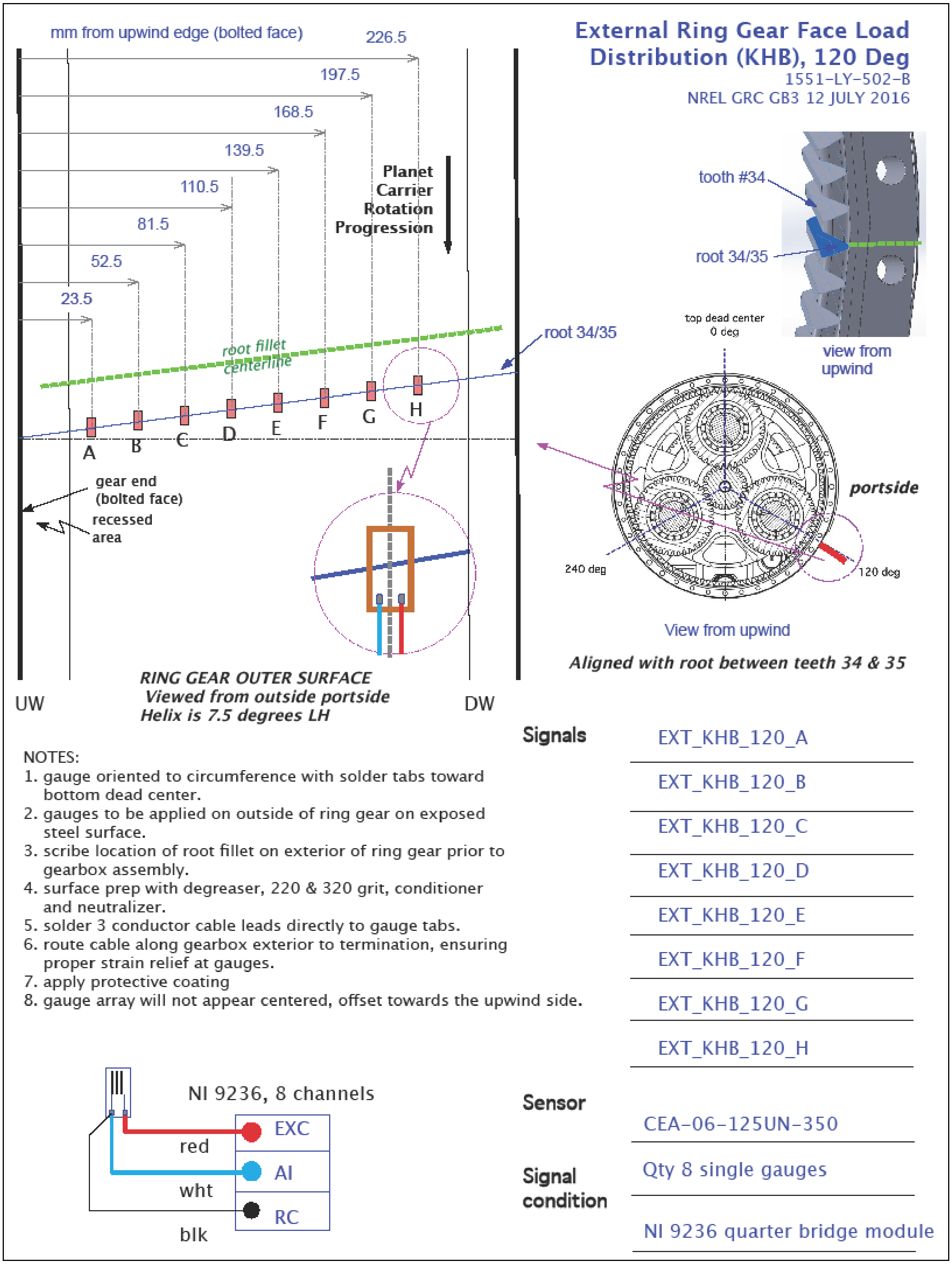
Figure C-12. Internal ring gear 240° face width load distribution. *Illustration by Romax Technology*



NOTES:
1. gauge oriented to circumference with solder tabs toward bottom dead center.
2. gauges to be applied on outside of ring gear on exposed steel surface.
3. scribe location of root fillet on exterior of ring gear prior to gearbox assembly.
4. surface prep with degreaser, 220 & 320 grit, conditioner and neutralizer.
5. solder 3 conductor cable leads directly to gauge tabs.
6. route cable along gearbox exterior to termination, ensuring proper strain relief at gauges.
7. apply protective coating
8. gauge array will not appear centered, offset towards the upwind side.

Signals	EXT_KHB_0_A EXT_KHB_0_B EXT_KHB_0_C EXT_KHB_0_D EXT_KHB_0_E EXT_KHB_0_F EXT_KHB_0_G EXT_KHB_0_H
Sensor	CEA-06-125UN-350 Qty 8 single gauges
Signal condition	NI 9236 quarter bridge module

Figure C-13. External ring gear 0° face width load distribution. *Illustration by Romax Technology*

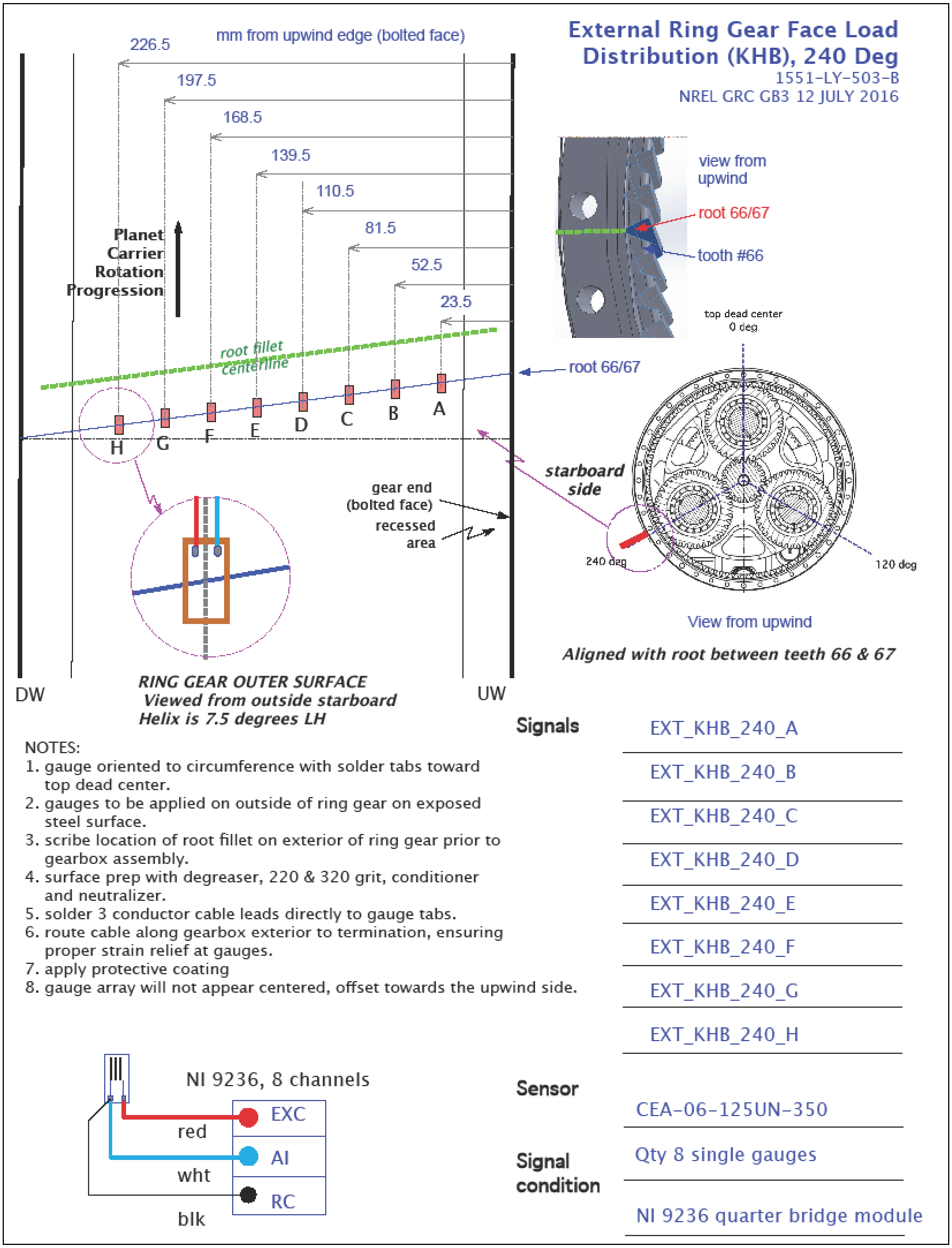


NOTES:

1. gauge oriented to circumference with solder tabs toward bottom dead center.
2. gauges to be applied on outside of ring gear on exposed steel surface.
3. scribe location of root fillet on exterior of ring gear prior to gearbox assembly.
4. surface prep with degreaser, 220 & 320 grit, conditioner and neutralizer.
5. solder 3 conductor cable leads directly to gauge tabs.
6. route cable along gearbox exterior to termination, ensuring proper strain relief at gauges.
7. apply protective coating
8. gauge array will not appear centered, offset towards the upwind side.

Signals	EXT_KHB_120_A
	EXT_KHB_120_B
	EXT_KHB_120_C
	EXT_KHB_120_D
	EXT_KHB_120_E
	EXT_KHB_120_F
	EXT_KHB_120_G
	EXT_KHB_120_H
Sensor	CEA-06-125UN-350
	Qty 8 single gauges
Signal condition	NI 9236 quarter bridge module

Figure C-14. External ring gear 120° face width load distribution. *Illustration by Romax Technology*



External Ring Gear Face Load Distribution (KHB), 240 Deg
1551-LY-503-B
NREL GRC GB3 12 JULY 2016

Aligned with root between teeth 66 & 67

RING GEAR OUTER SURFACE
Viewed from outside starboard
Helix is 7.5 degrees LH

NOTES:

1. gauge oriented to circumference with solder tabs toward top dead center.
2. gauges to be applied on outside of ring gear on exposed steel surface.
3. scribe location of root fillet on exterior of ring gear prior to gearbox assembly.
4. surface prep with degreaser, 220 & 320 grit, conditioner and neutralizer.
5. solder 3 conductor cable leads directly to gauge tabs.
6. route cable along gearbox exterior to termination, ensuring proper strain relief at gauges.
7. apply protective coating
8. gauge array will not appear centered, offset towards the upwind side.

Signals

EXT_KHB_240_A
EXT_KHB_240_B
EXT_KHB_240_C
EXT_KHB_240_D
EXT_KHB_240_E
EXT_KHB_240_F
EXT_KHB_240_G
EXT_KHB_240_H

NI 9236, 8 channels

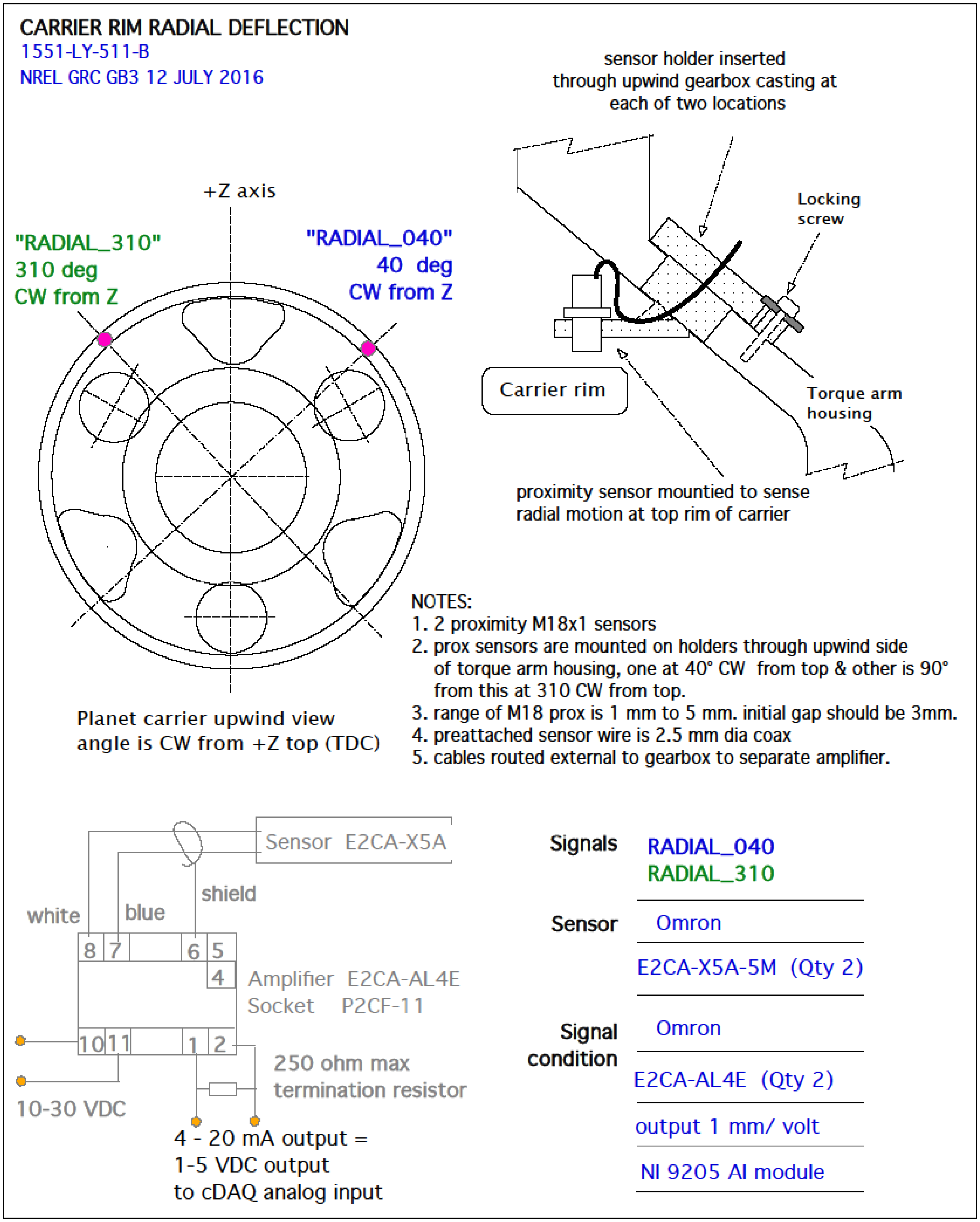
Sensor

CEA-06-125UN-350
Qty 8 single gauges

Signal condition

NI 9236 quarter bridge module

Figure C-15. External ring gear 240° face width load distribution. *Illustration by Romax Technology*

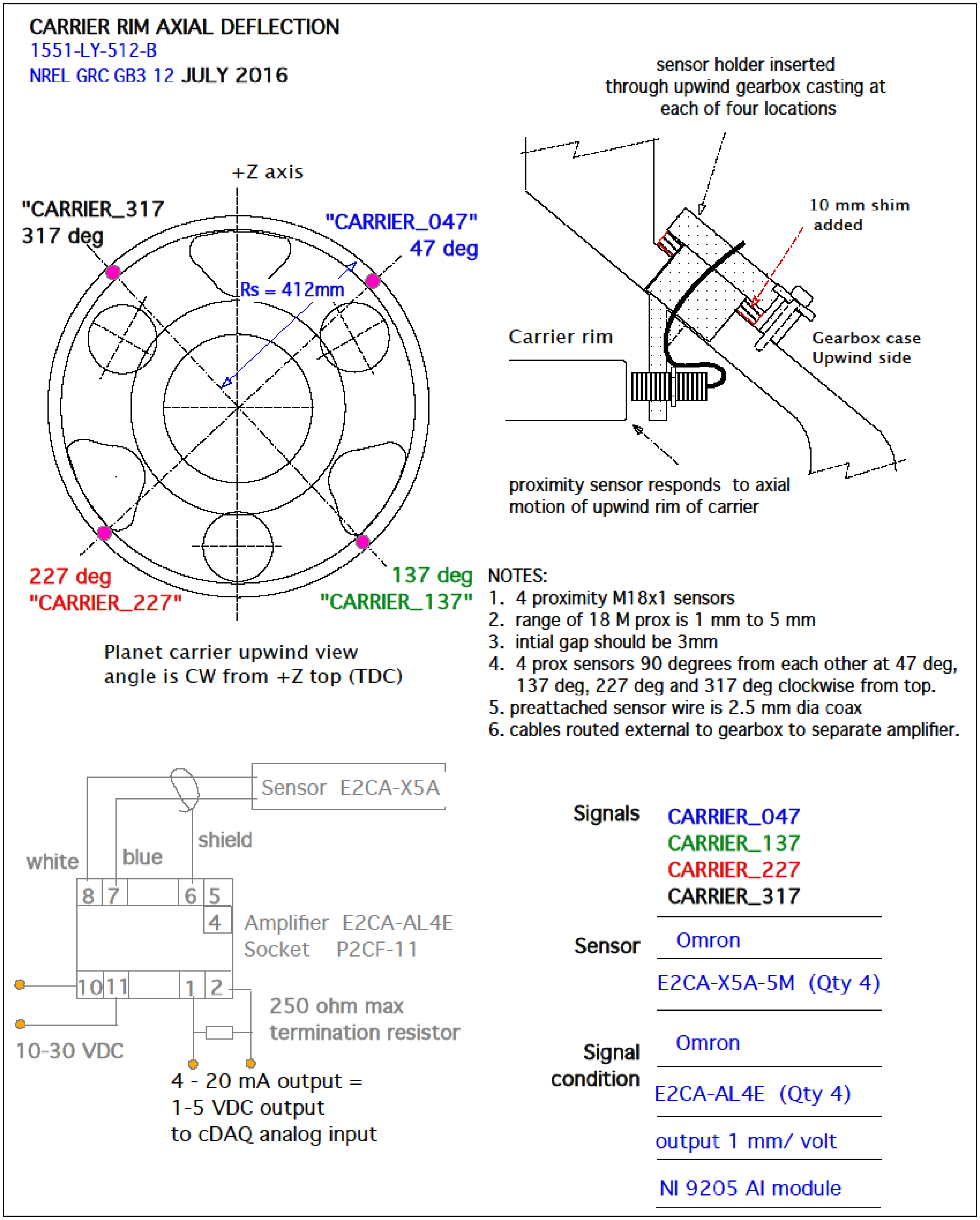


NOTES:

1. 2 proximity M18x1 sensors
2. prox sensors are mounted on holders through upwind side of torque arm housing, one at 40° CW from top & other is 90° from this at 310 CW from top.
3. range of M18 prox is 1 mm to 5 mm. initial gap should be 3mm.
4. preattached sensor wire is 2.5 mm dia coax
5. cables routed external to gearbox to separate amplifier.

Signals	RADIAL_040 RADIAL_310
Sensor	Omron
	E2CA-X5A-5M (Qty 2)
Signal condition	Omron
	E2CA-AL4E (Qty 2)
	output 1 mm/ volt
	NI 9205 AI module

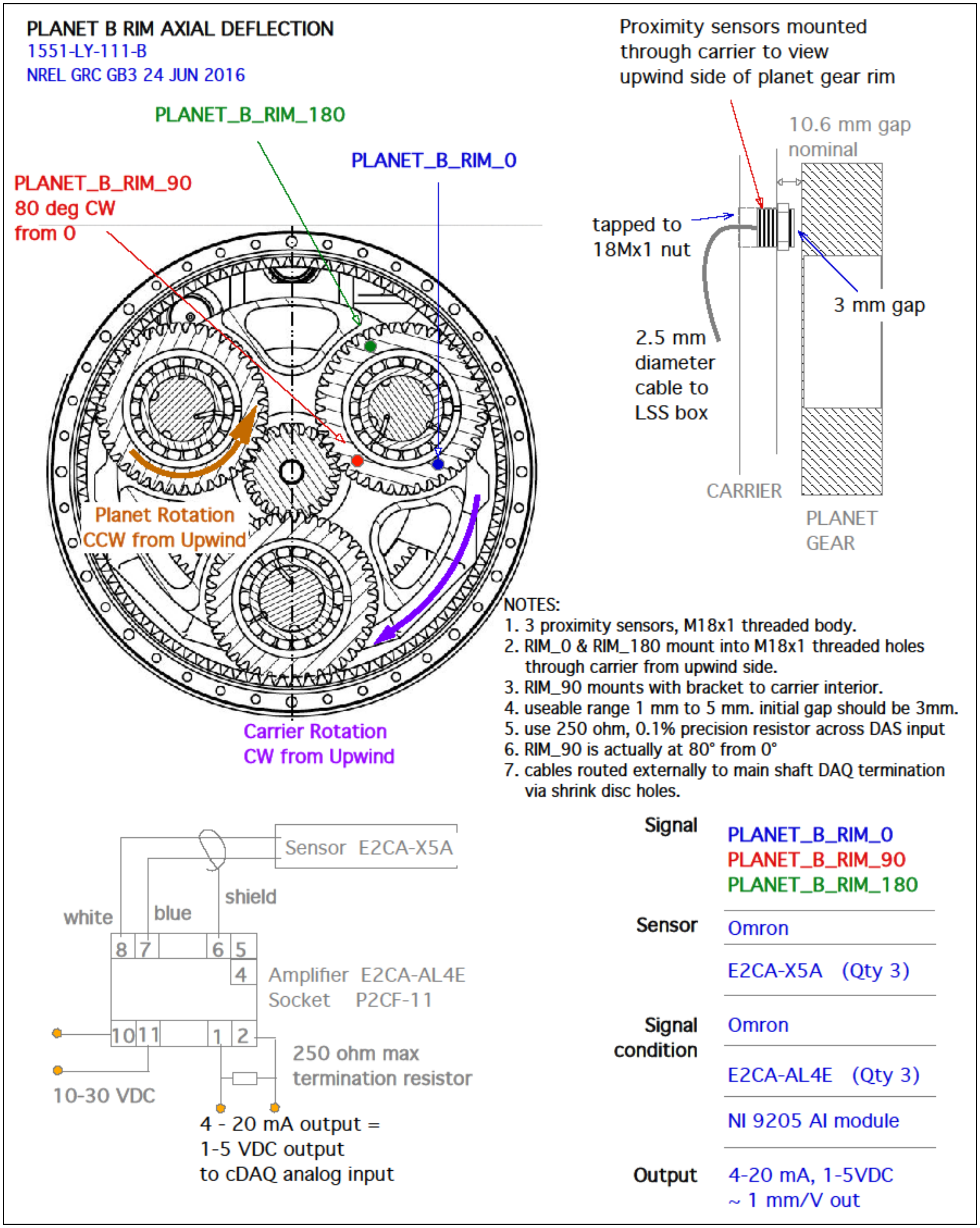
Figure C-16. Carrier-rim radial displacement. *Illustration by Romax Technology*



NOTES:
1. 4 proximity M18x1 sensors
2. range of 18 M prox is 1 mm to 5 mm
3. intial gap should be 3mm
4. 4 prox sensors 90 degrees from each other at 47 deg, 137 deg, 227 deg and 317 deg clockwise from top.
5. preattached sensor wire is 2.5 mm dia coax
6. cables routed external to gearbox to separate amplifier.

Signals	CARRIER_047 CARRIER_137 CARRIER_227 CARRIER_317
Sensor	Omron E2CA-X5A-5M (Qty 4)
Signal condition	Omron E2CA-AL4E (Qty 4) output 1 mm/ volt NI 9205 AI module

Figure C-17. Carrier-rim axial displacement. *Illustration by Romax Technology*

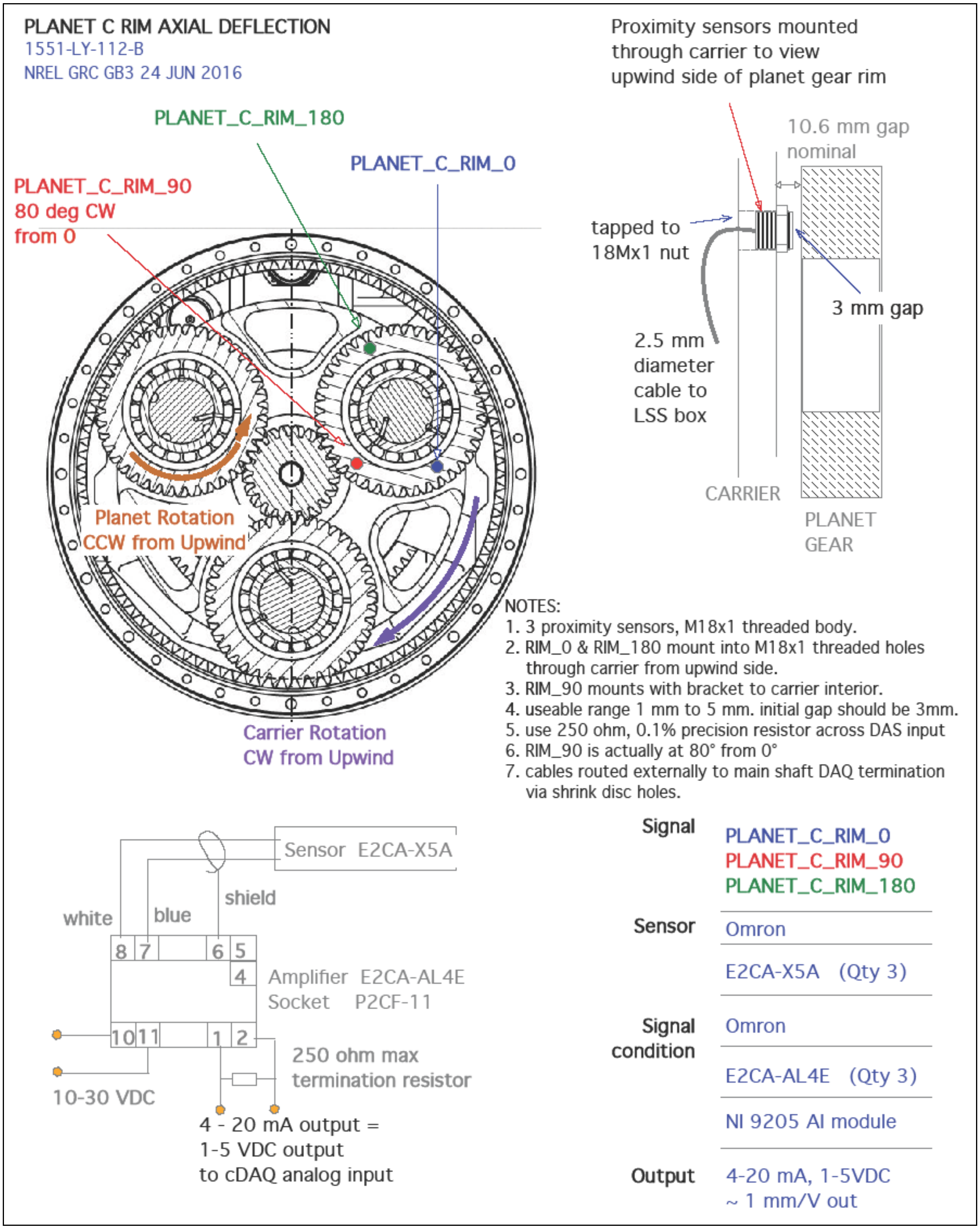


NOTES:

1. 3 proximity sensors, M18x1 threaded body.
2. RIM_0 & RIM_180 mount into M18x1 threaded holes through carrier from upwind side.
3. RIM_90 mounts with bracket to carrier interior.
4. useable range 1 mm to 5 mm. initial gap should be 3mm.
5. use 250 ohm, 0.1% precision resistor across DAS input
6. RIM_90 is actually at 80° from 0°
7. cables routed externally to main shaft DAQ termination via shrink disc holes.

Signal	PLANET_B_RIM_0 PLANET_B_RIM_90 PLANET_B_RIM_180
Sensor	Omron
	E2CA-X5A (Qty 3)
Signal condition	Omron
	E2CA-AL4E (Qty 3)
	NI 9205 AI module
Output	4-20 mA, 1-5VDC ~ 1 mm/V out

Figure C-18. Planet gear B rim deflection. *Illustration by Romax Technology*

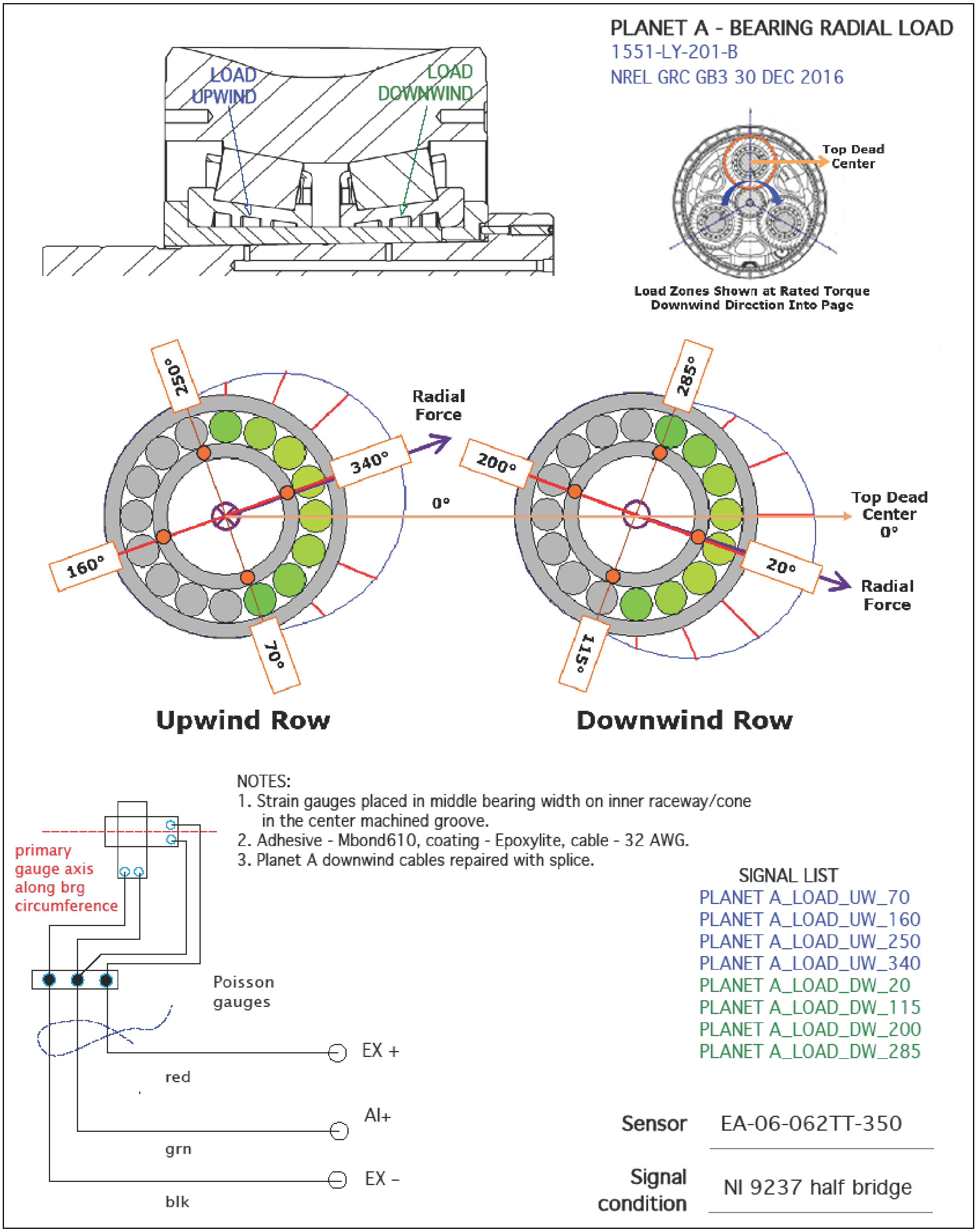


NOTES:

1. 3 proximity sensors, M18x1 threaded body.
2. RIM_0 & RIM_180 mount into M18x1 threaded holes through carrier from upwind side.
3. RIM_90 mounts with bracket to carrier interior.
4. useable range 1 mm to 5 mm. initial gap should be 3mm.
5. use 250 ohm, 0.1% precision resistor across DAS input
6. RIM_90 is actually at 80° from 0°
7. cables routed externally to main shaft DAQ termination via shrink disc holes.

Signal	PLANET_C_RIM_0 PLANET_C_RIM_90 PLANET_C_RIM_180
Sensor	Omron
	E2CA-X5A (Qty 3)
Signal condition	Omron
	E2CA-AL4E (Qty 3)
	NI 9205 AI module
Output	4-20 mA, 1-5VDC ~ 1 mm/V out

Figure C-19. Planet gear C rim deflection. *Illustration by Romax Technology*

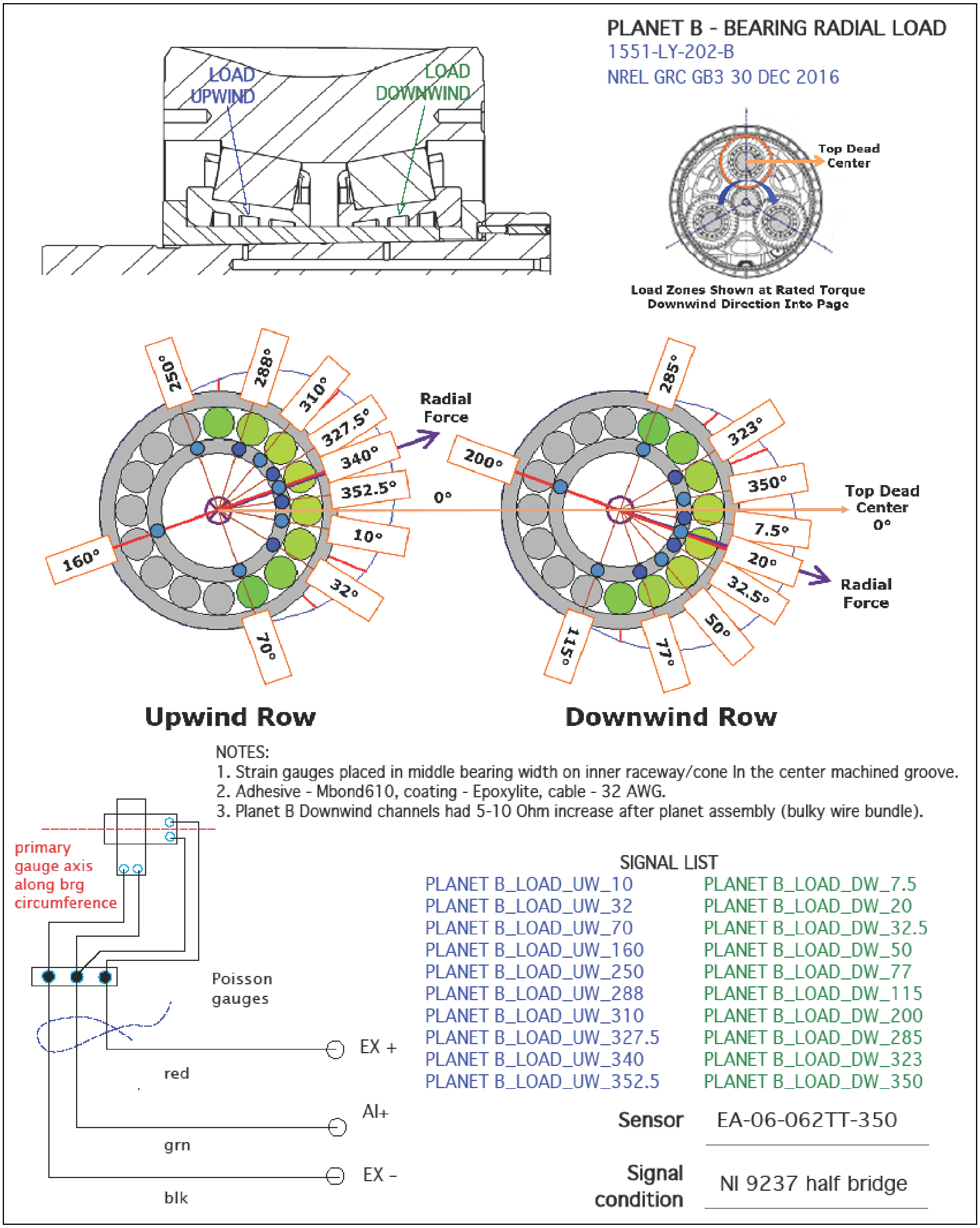


NOTES:
1. Strain gauges placed in middle bearing width on inner raceway/cone in the center machined groove.
2. Adhesive - Mbond610, coating - Epoxylite, cable - 32 AWG.
3. Planet A downwind cables repaired with splice.

SIGNAL LIST
PLANET A_LOAD_UW_70
PLANET A_LOAD_UW_160
PLANET A_LOAD_UW_250
PLANET A_LOAD_UW_340
PLANET A_LOAD_DW_20
PLANET A_LOAD_DW_115
PLANET A_LOAD_DW_200
PLANET A_LOAD_DW_285

Sensor	EA-06-062TT-350
Signal condition	NI 9237 half bridge

Figure C-20. Planet-bearing A instrumentation. *Illustration by Romax Technology*



PLANET B - BEARING RADIAL LOAD
1551-LY-202-B
NREL GRC GB3 30 DEC 2016

NOTES:
1. Strain gauges placed in middle bearing width on inner raceway/cone In the center machined groove.
2. Adhesive - Mbond610, coating - Epoxylite, cable - 32 AWG.
3. Planet B Downwind channels had 5-10 Ohm increase after planet assembly (bulky wire bundle).

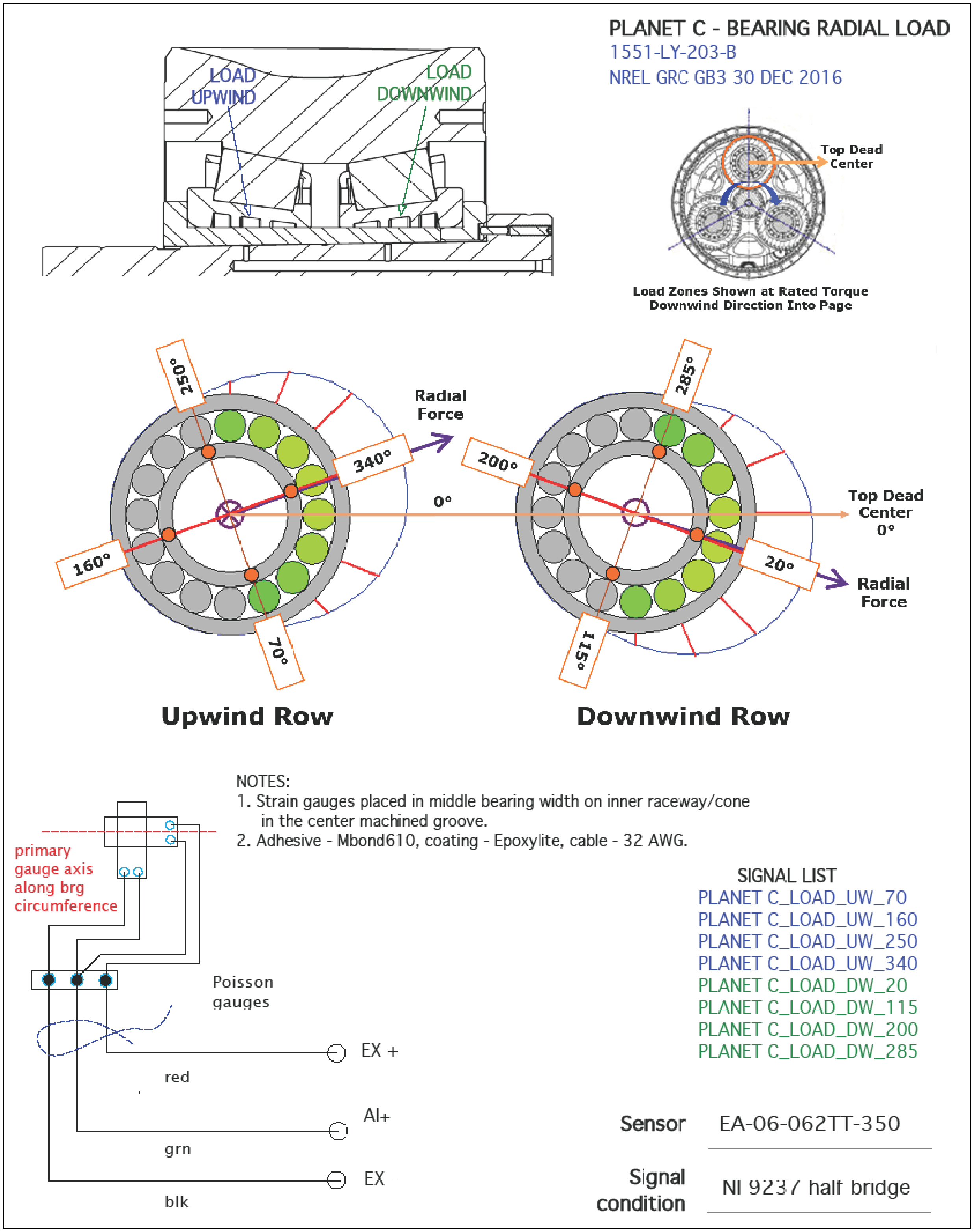
SIGNAL LIST

PLANET B_LOAD_UW_10
PLANET B_LOAD_UW_32
PLANET B_LOAD_UW_70
PLANET B_LOAD_UW_160
PLANET B_LOAD_UW_250
PLANET B_LOAD_UW_288
PLANET B_LOAD_UW_310
PLANET B_LOAD_UW_327.5
PLANET B_LOAD_UW_340
PLANET B_LOAD_UW_352.5

PLANET B_LOAD_DW_7.5
PLANET B_LOAD_DW_20
PLANET B_LOAD_DW_32.5
PLANET B_LOAD_DW_50
PLANET B_LOAD_DW_77
PLANET B_LOAD_DW_115
PLANET B_LOAD_DW_200
PLANET B_LOAD_DW_285
PLANET B_LOAD_DW_323
PLANET B_LOAD_DW_350

Sensor	EA-06-062TT-350
Signal condition	NI 9237 half bridge

Figure C-21. Planet-bearing B instrumentation. *Illustration by Romax Technology*

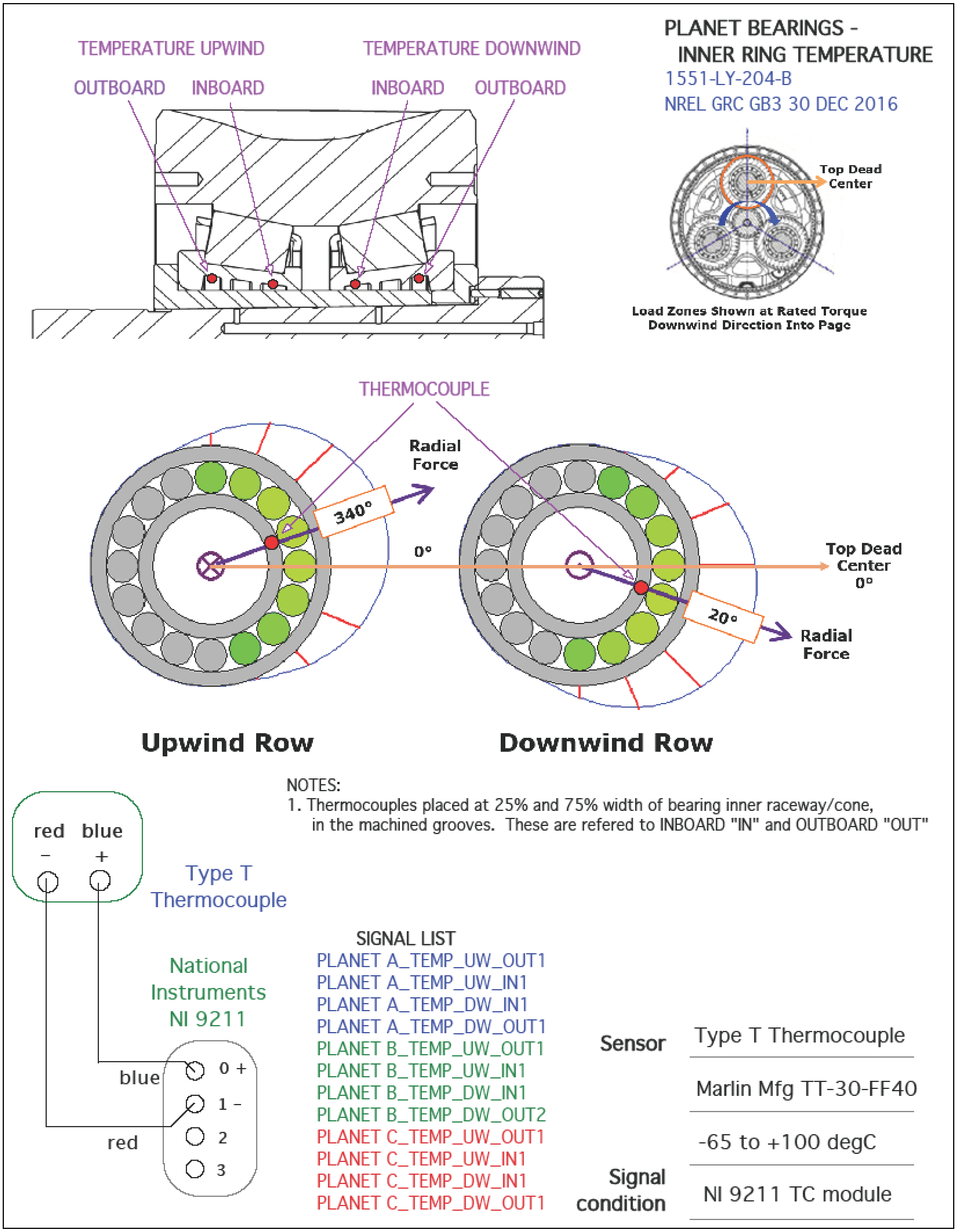


NOTES:
1. Strain gauges placed in middle bearing width on inner raceway/cone in the center machined groove.
2. Adhesive - Mbond610, coating - Epoxylite, cable - 32 AWG.

SIGNAL LIST
PLANET C_LOAD_UW_70
PLANET C_LOAD_UW_160
PLANET C_LOAD_UW_250
PLANET C_LOAD_UW_340
PLANET C_LOAD_DW_20
PLANET C_LOAD_DW_115
PLANET C_LOAD_DW_200
PLANET C_LOAD_DW_285

Sensor	EA-06-062TT-350
Signal condition	NI 9237 half bridge

Figure C-22. Planet-bearing C instrumentation. *Illustration by Romax Technology*



NOTES:

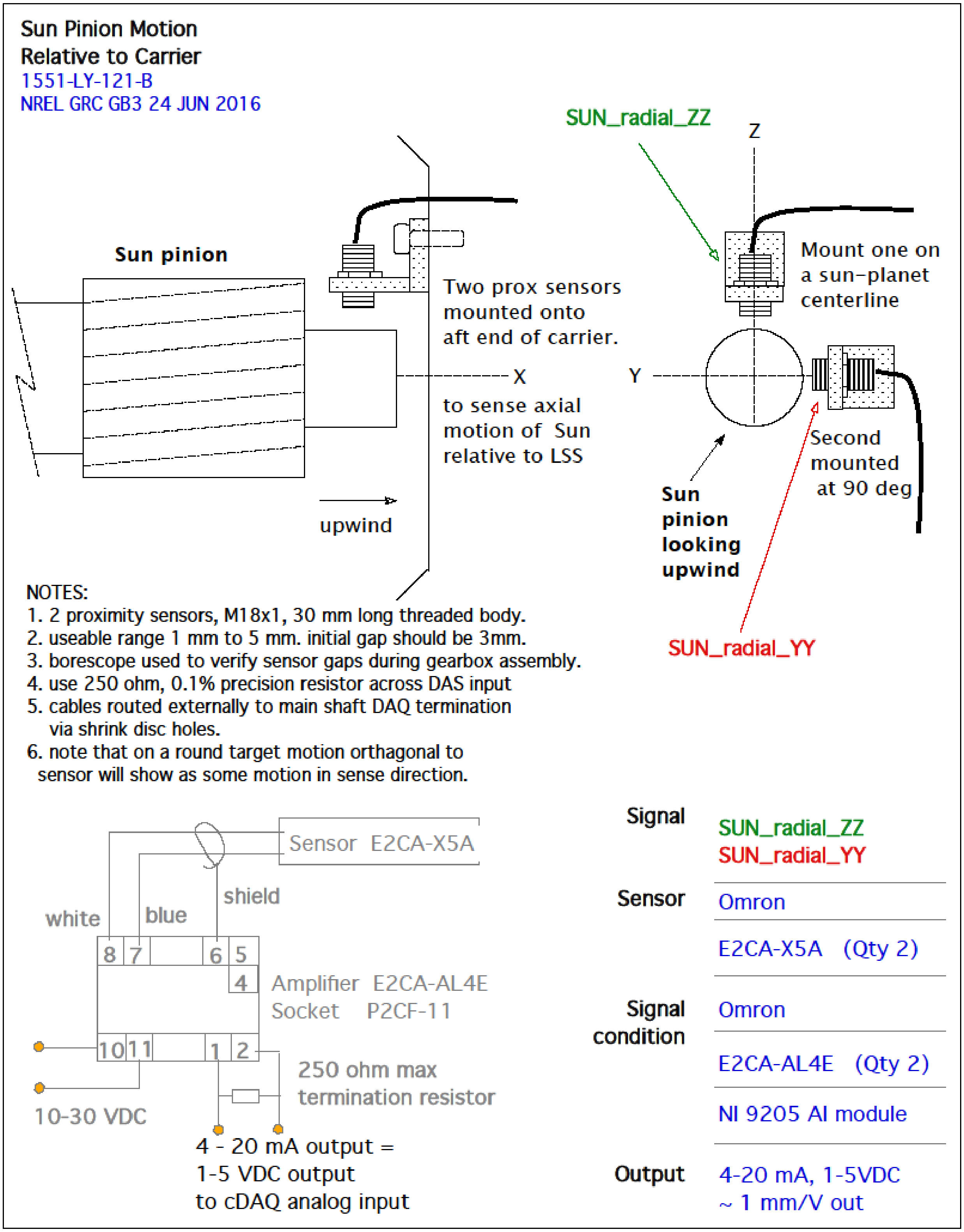
1. Thermocouples placed at 25% and 75% width of bearing inner raceway/cone, in the machined grooves. These are refered to INBOARD "IN" and OUTBOARD "OUT"

SIGNAL LIST

PLANET A_TEMP_UW_OUT1
PLANET A_TEMP_UW_IN1
PLANET A_TEMP_DW_IN1
PLANET A_TEMP_DW_OUT1
PLANET B_TEMP_UW_OUT1
PLANET B_TEMP_UW_IN1
PLANET B_TEMP_DW_IN1
PLANET B_TEMP_DW_OUT2
PLANET C_TEMP_UW_OUT1
PLANET C_TEMP_UW_IN1
PLANET C_TEMP_DW_IN1
PLANET C_TEMP_DW_OUT1

Sensor	Type T Thermocouple
	Marlin Mfg TT-30-FF40
	-65 to +100 degC
Signal condition	NI 9211 TC module

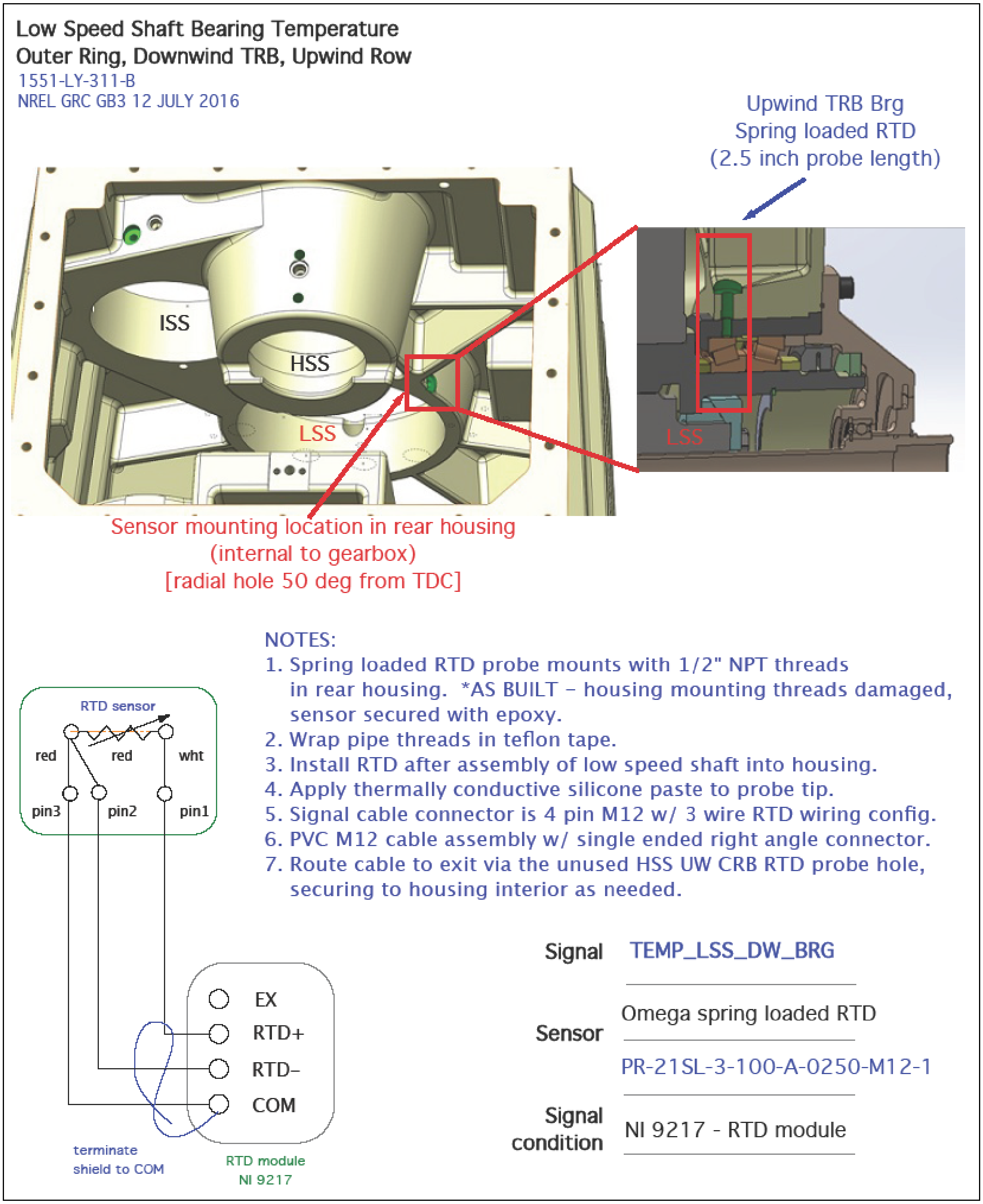
Figure C-23. Planet-bearing temperatures. *Illustration by Romax Technology*



NOTES:
1. 2 proximity sensors, M18x1, 30 mm long threaded body.
2. useable range 1 mm to 5 mm. initial gap should be 3mm.
3. borescope used to verify sensor gaps during gearbox assembly.
4. use 250 ohm, 0.1% precision resistor across DAS input
5. cables routed externally to main shaft DAQ termination via shrink disc holes.
6. note that on a round target motion orthogonal to sensor will show as some motion in sense direction.

Signal	SUN_radial_ZZ SUN_radial_YY
Sensor	Omron
	E2CA-X5A (Qty 2)
Signal condition	Omron
	E2CA-AL4E (Qty 2)
	NI 9205 AI module
Output	4-20 mA, 1-5VDC ~ 1 mm/V out

Figure C-24. Sun pinion radial motion. *Illustration by Romax Technology*



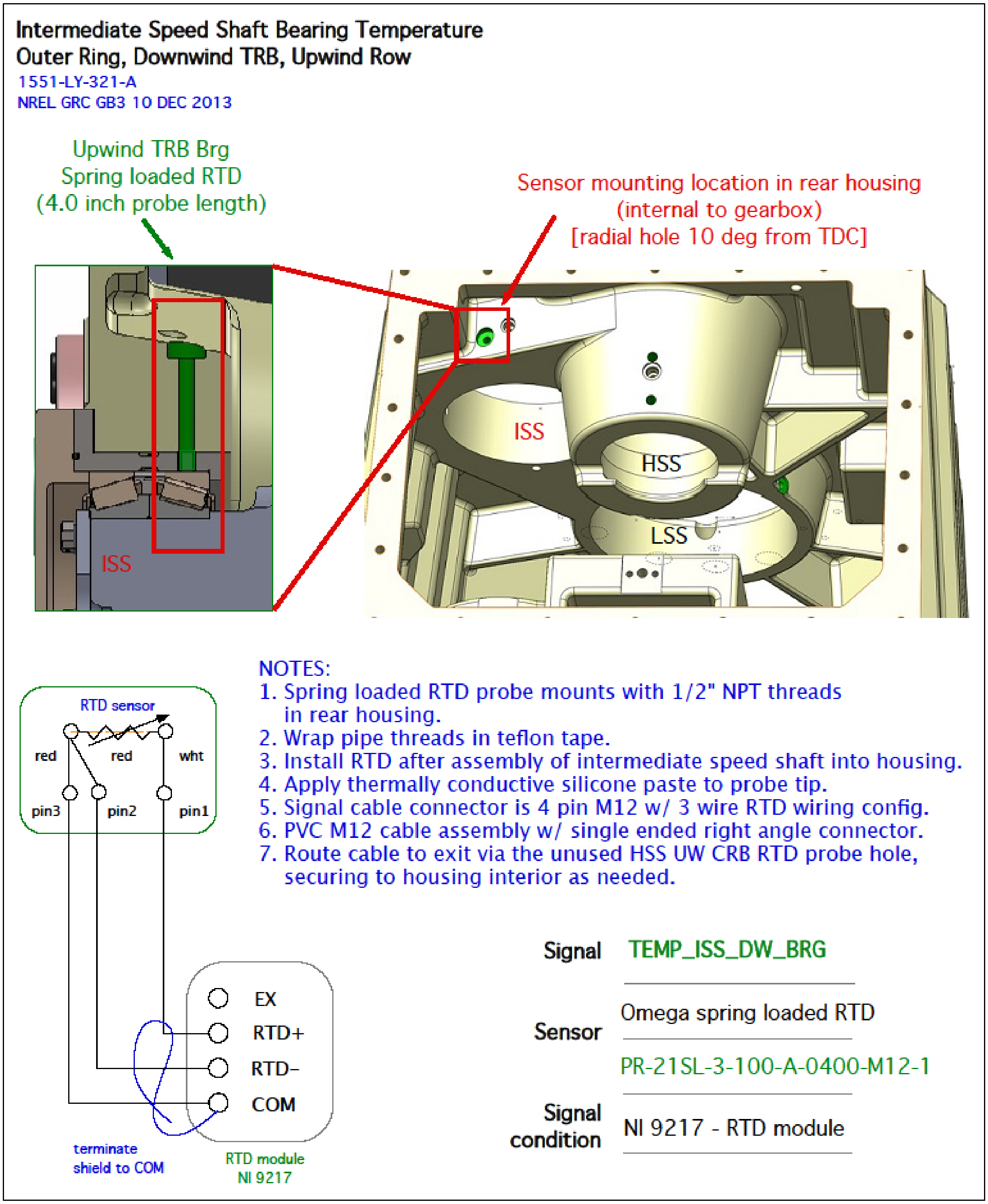
Low Speed Shaft Bearing Temperature
Outer Ring, Downwind TRB, Upwind Row
1551-LY-311-B
NREL GRC GB3 12 JULY 2016

NOTES:

1. Spring loaded RTD probe mounts with 1/2" NPT threads in rear housing. *AS BUILT – housing mounting threads damaged, sensor secured with epoxy.
2. Wrap pipe threads in teflon tape.
3. Install RTD after assembly of low speed shaft into housing.
4. Apply thermally conductive silicone paste to probe tip.
5. Signal cable connector is 4 pin M12 w/ 3 wire RTD wiring config.
6. PVC M12 cable assembly w/ single ended right angle connector.
7. Route cable to exit via the unused HSS UW CRB RTD probe hole, securing to housing interior as needed.

Signal	TEMP_LSS_DW_BRG
Sensor	Omega spring loaded RTD PR-21SL-3-100-A-0250-M12-1
Signal condition	NI 9217 - RTD module

Figure C-25. Low-speed shaft bearing temperature. *Illustration by Romax Technology*

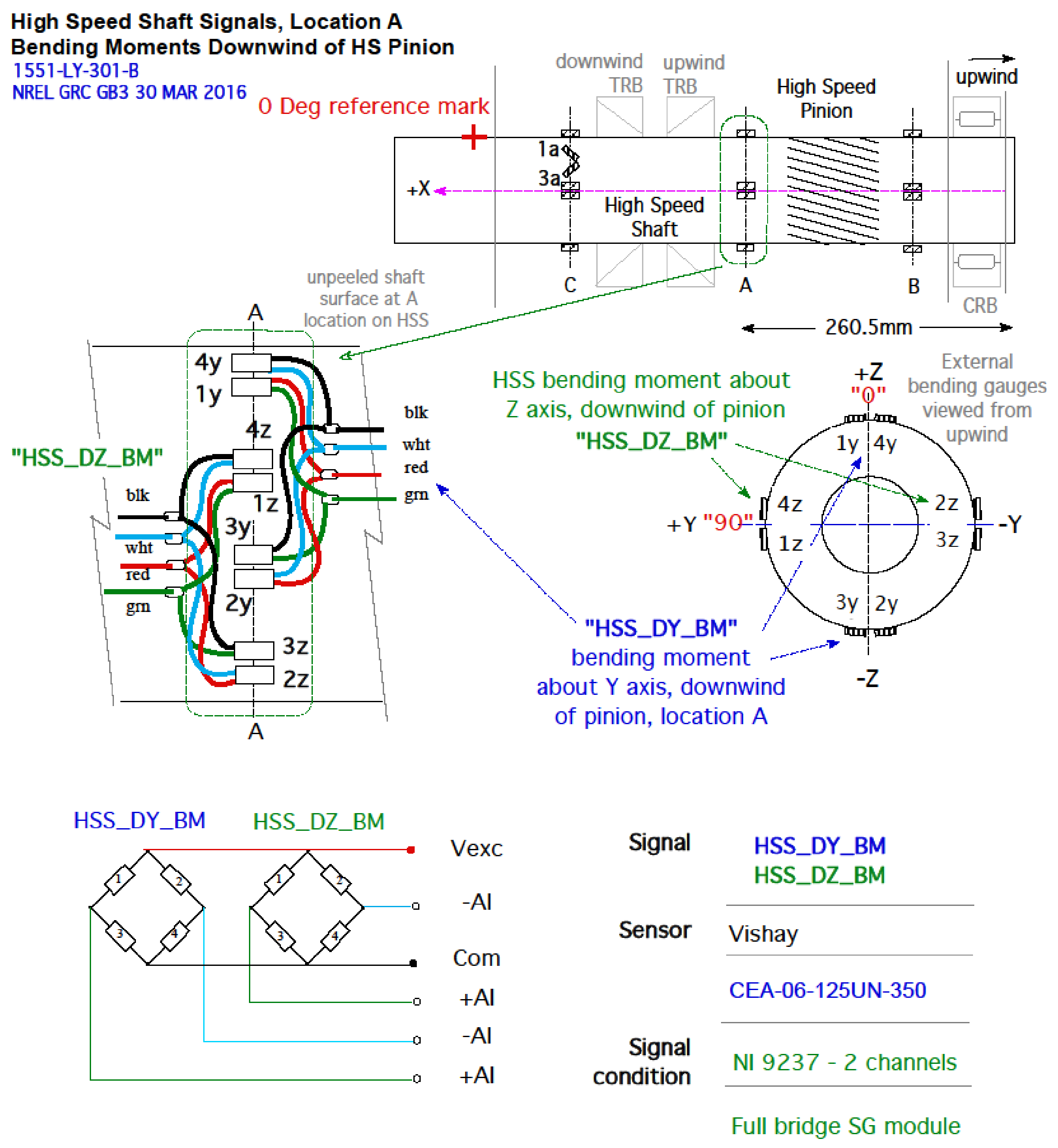


Intermediate Speed Shaft Bearing Temperature
Outer Ring, Downwind TRB, Upwind Row
1551-LY-321-A
NREL GRC GB3 10 DEC 2013

NOTES:
1. Spring loaded RTD probe mounts with 1/2" NPT threads in rear housing.
2. Wrap pipe threads in teflon tape.
3. Install RTD after assembly of intermediate speed shaft into housing.
4. Apply thermally conductive silicone paste to probe tip.
5. Signal cable connector is 4 pin M12 w/ 3 wire RTD wiring config.
6. PVC M12 cable assembly w/ single ended right angle connector.
7. Route cable to exit via the unused HSS UW CRB RTD probe hole, securing to housing interior as needed.

Signal	TEMP_ISS_DW_BRG
Sensor	Omega spring loaded RTD PR-21SL-3-100-A-0400-M12-1
Signal condition	NI 9217 - RTD module

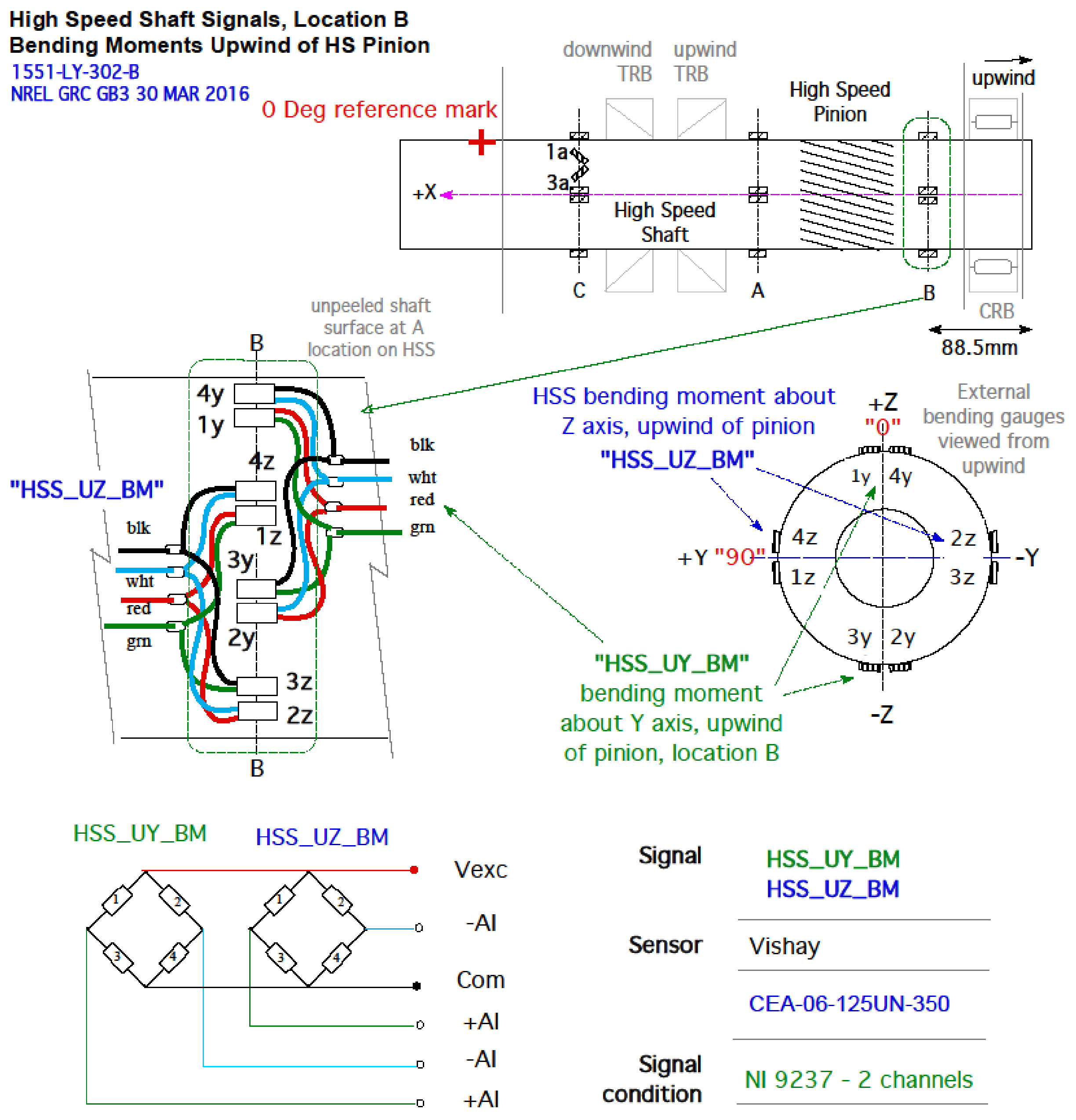
Figure C-26. Intermediate-speed shaft bearing temperature. *Illustration by Romax Technology*



Signal	HSS_DY_BM HSS_DZ_BM
Sensor	Vishay
	CEA-06-125UN-350
Signal condition	NI 9237 - 2 channels
	Full bridge SG module

NOTES:
1. +Z is located by "0" degree reference mark engraved on downwind end of shaft. The +Y location is engraved "90".
2. Use solder tabs bonded to the shaft to complete full bridge wiring prior to routing cables to HSS slip ring via radial holes within shaft.
3. Use jumper wires, 3 conductor and 4 conductor cables for lead wires.
4. Cover entire shaft circumference with a layer of protective coating.
5. Refer to 1551-LY-901 for HSS wiring schematic through slip ring.

Figure C-27. High-speed shaft bending at location A. *Illustration by Romax Technology*

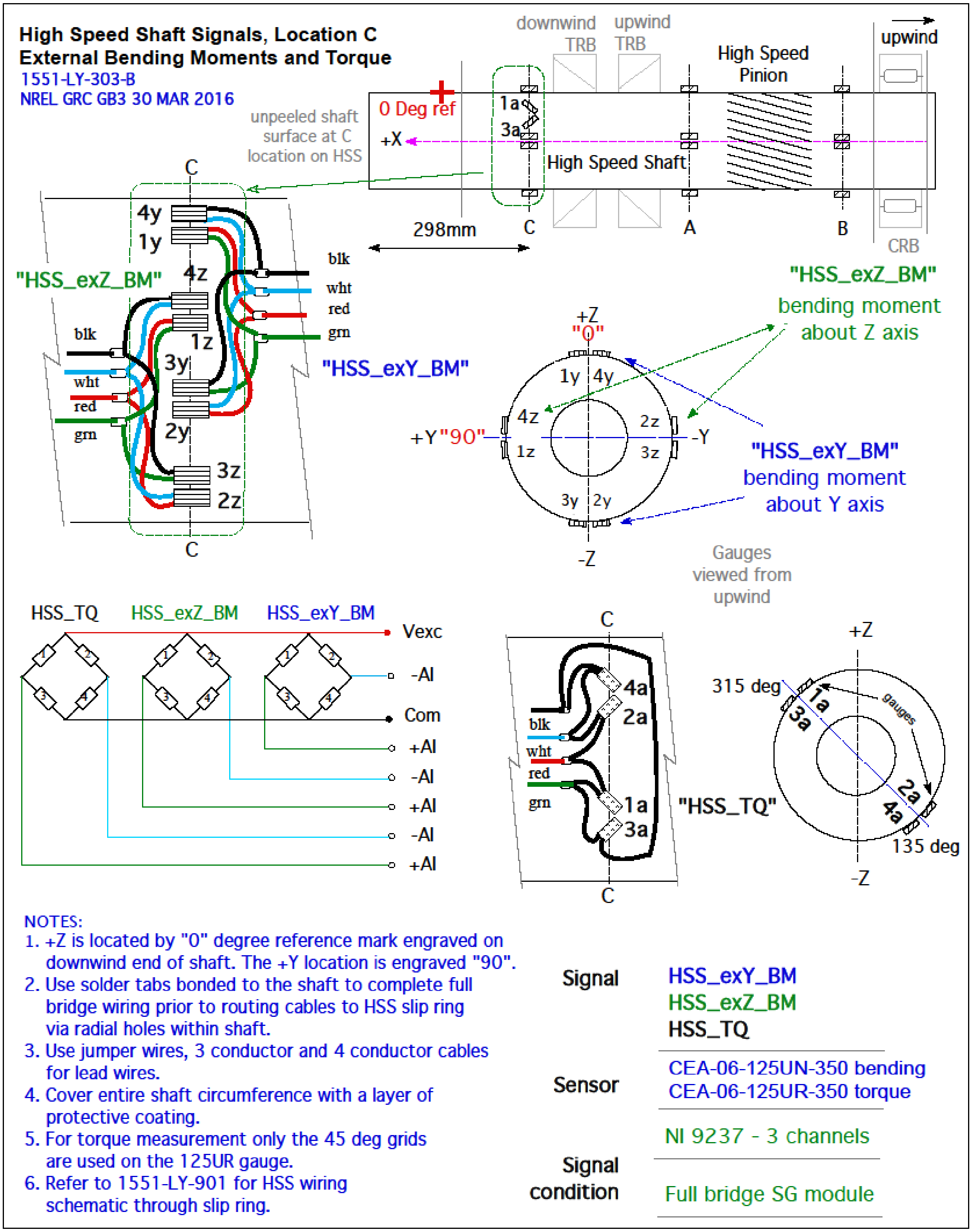


Signal	HSS_UY_BM HSS_UZ_BM
Sensor	Vishay
	CEA-06-125UN-350
Signal condition	NI 9237 - 2 channels
	Full bridge SG module

NOTES:

1. +Z is located by "0" degree reference mark engraved on downwind end of shaft. The +Y location is engraved "90".
2. Use solder tabs bonded to the shaft to complete full bridge wiring prior to routing cables to HSS slip ring via radial holes within shaft.
3. Use jumper wires, 3 conductor and 4 conductor cables for lead wires.
4. Cover entire shaft circumference with a layer of protective coating.
5. Refer to 1551-LY-901 for HSS wiring schematic through slip ring.

Figure C-28. High-speed shaft bending at location B. *Illustration by Romax Technology*

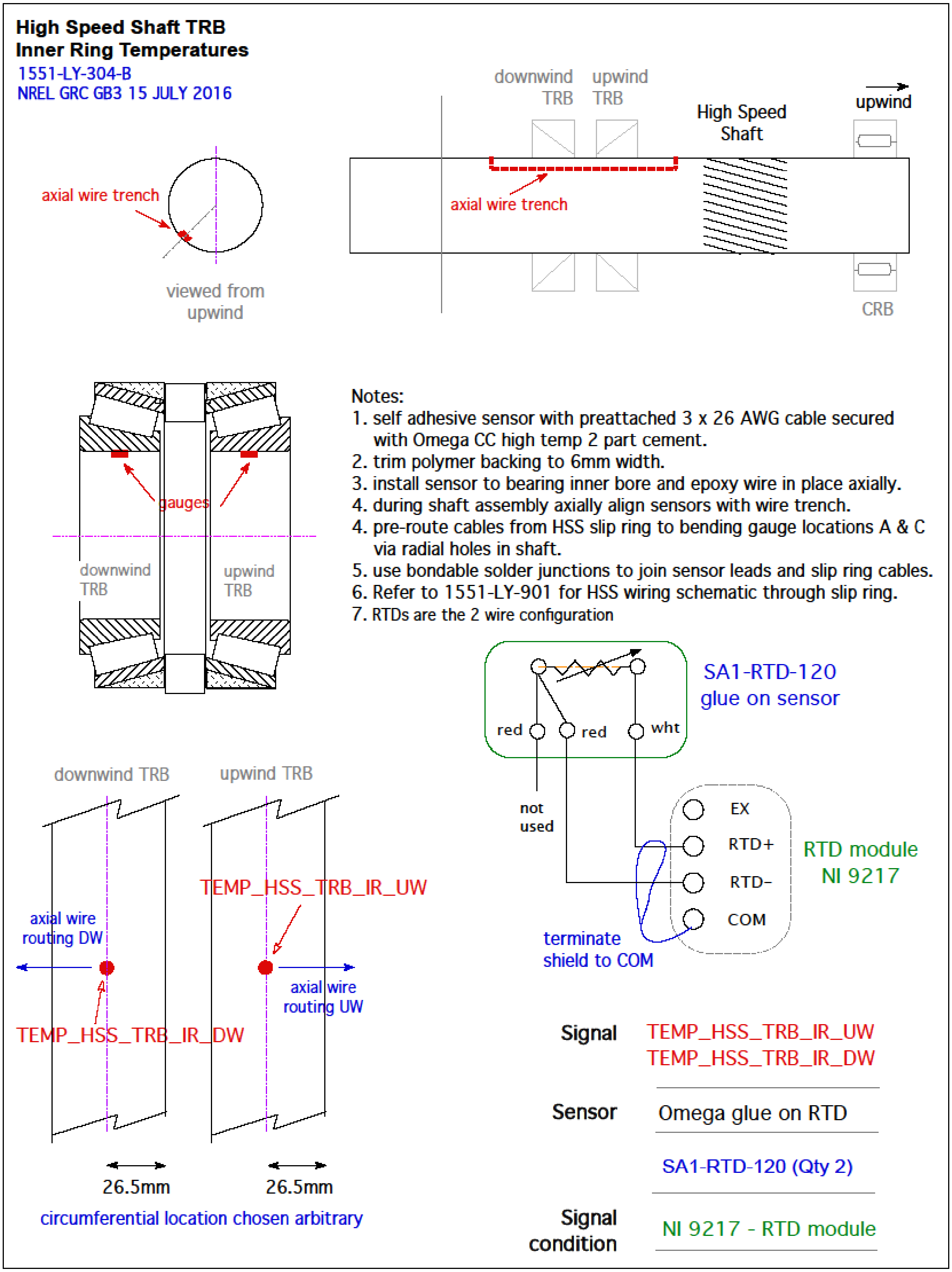


NOTES:

1. +Z is located by "0" degree reference mark engraved on downwind end of shaft. The +Y location is engraved "90".
2. Use solder tabs bonded to the shaft to complete full bridge wiring prior to routing cables to HSS slip ring via radial holes within shaft.
3. Use jumper wires, 3 conductor and 4 conductor cables for lead wires.
4. Cover entire shaft circumference with a layer of protective coating.
5. For torque measurement only the 45 deg grids are used on the 125UR gauge.
6. Refer to 1551-LY-901 for HSS wiring schematic through slip ring.

Signal	HSS_exY_BM HSS_exZ_BM HSS_TQ
Sensor	CEA-06-125UN-350 bending CEA-06-125UR-350 torque
Signal condition	NI 9237 - 3 channels Full bridge SG module

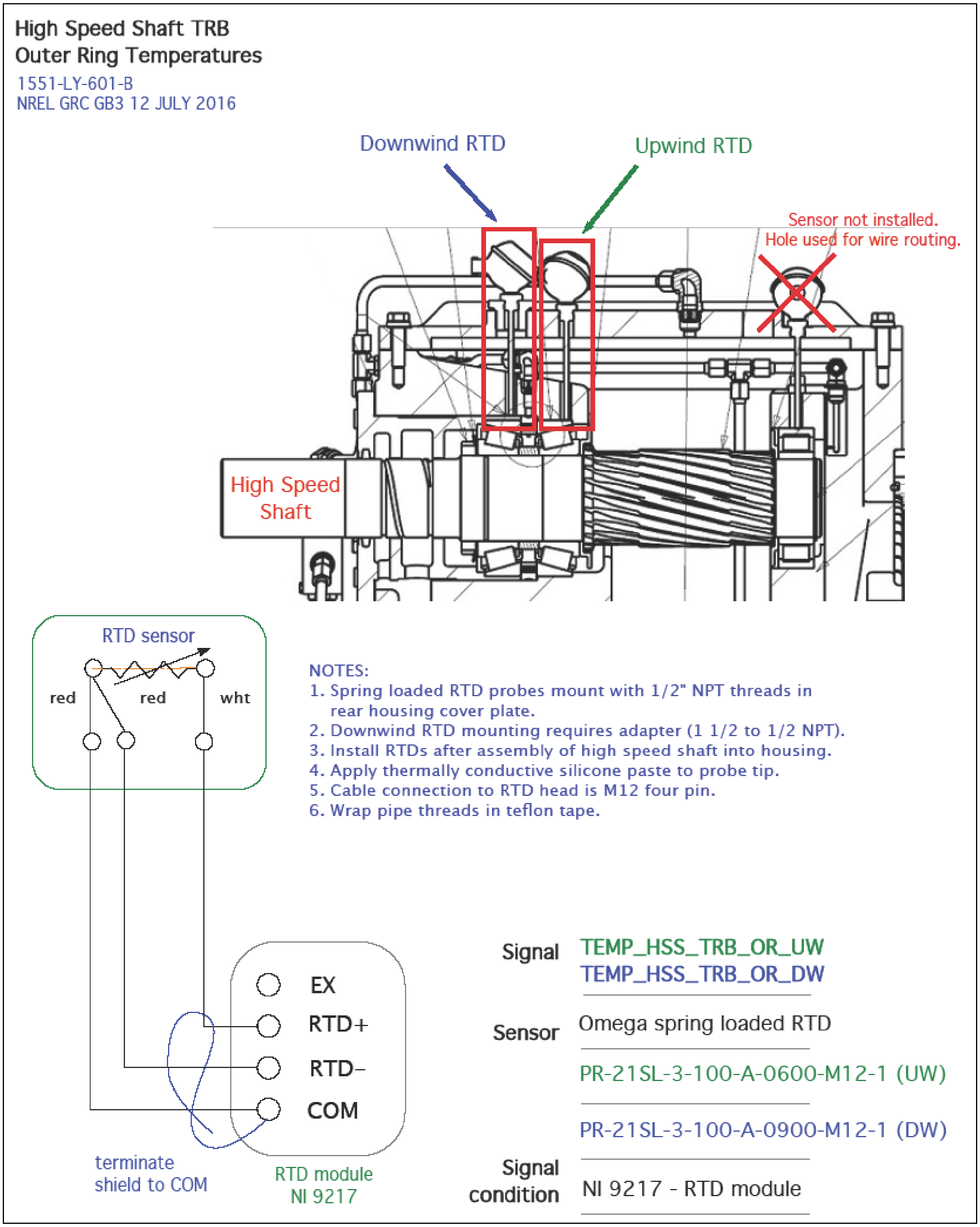
Figure C-29. High-speed shaft bending and torque at location C. *Illustration by Romax Technology*



Notes:
1. self adhesive sensor with preattached 3 x 26 AWG cable secured with Omega CC high temp 2 part cement.
2. trim polymer backing to 6mm width.
3. install sensor to bearing inner bore and epoxy wire in place axially.
4. during shaft assembly axially align sensors with wire trench.
4. pre-route cables from HSS slip ring to bending gauge locations A & C via radial holes in shaft.
5. use bondable solder junctions to join sensor leads and slip ring cables.
6. Refer to 1551-LY-901 for HSS wiring schematic through slip ring.
7. RTDs are the 2 wire configuration

Signal	TEMP_HSS_TRB_IR_UW TEMP_HSS_TRB_IR_DW
Sensor	Omega glue on RTD
	SA1-RTD-120 (Qty 2)
Signal condition	NI 9217 - RTD module

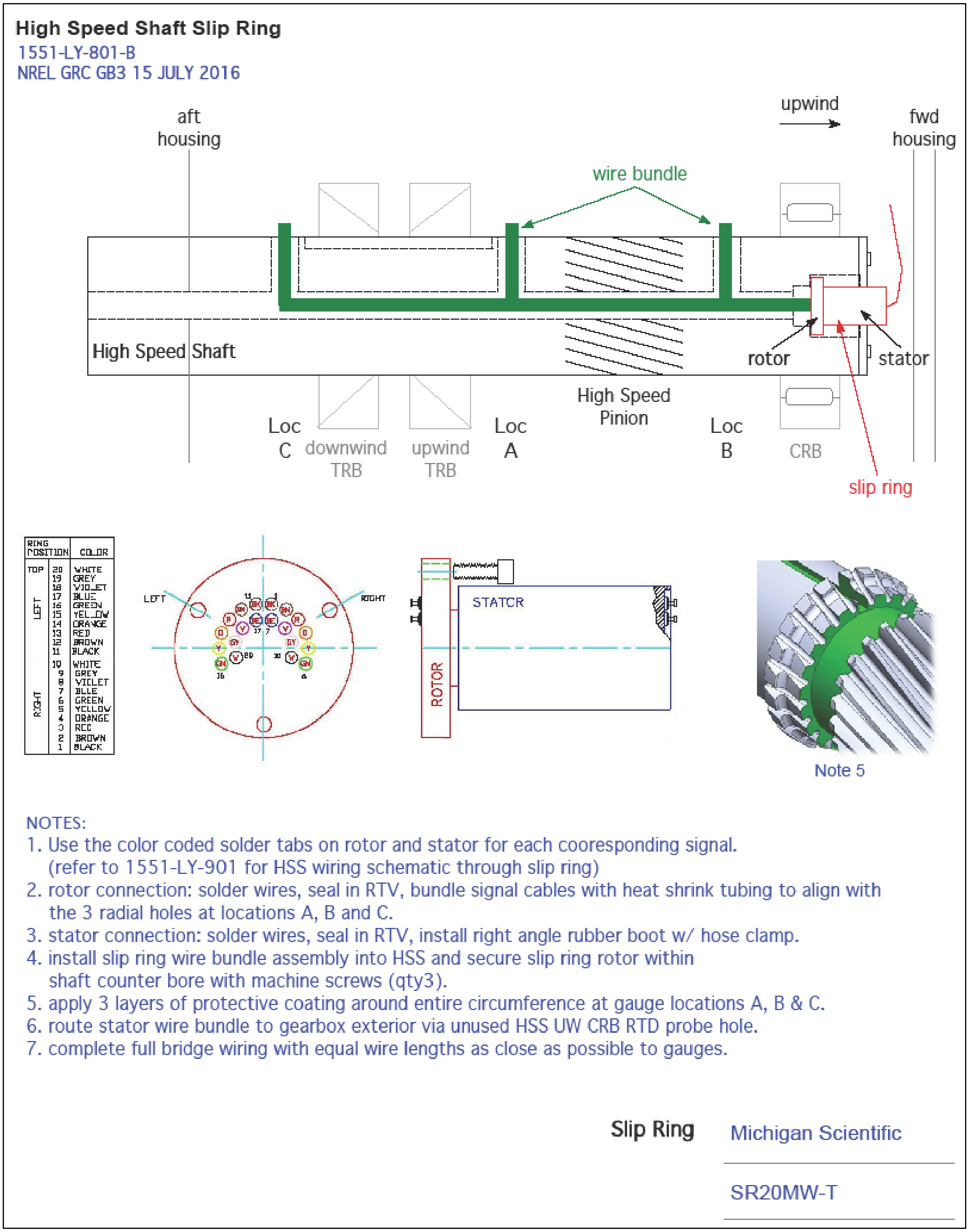
Figure C-30. High-speed shaft bearing inner ring temperature. *Illustration by Romax Technology*



NOTES:
1. Spring loaded RTD probes mount with 1/2" NPT threads in rear housing cover plate.
2. Downwind RTD mounting requires adapter (1 1/2 to 1/2 NPT).
3. Install RTDs after assembly of high speed shaft into housing.
4. Apply thermally conductive silicone paste to probe tip.
5. Cable connection to RTD head is M12 four pin.
6. Wrap pipe threads in teflon tape.

Signal	TEMP_HSS_TRB_OR_UW TEMP_HSS_TRB_OR_DW
Sensor	Omega spring loaded RTD
	PR-21SL-3-100-A-0600-M12-1 (UW)
	PR-21SL-3-100-A-0900-M12-1 (DW)
Signal condition	NI 9217 - RTD module

Figure C-31. High-speed shaft bearing outer ring temperature. *Illustration by Romax Technology*



RING POSITION		COLOR
TOP	20	WHITE
LEFT	19	GREY
	18	VIOLET
	17	BLUE
	16	GREEN
	15	YELLOW
	14	ORANGE
	13	RED
	12	BROWN
	11	BLACK
RIGHT	10	WHITE
	9	GREY
	8	VIOLET
	7	BLUE
	6	GREEN
	5	YELLOW
	4	ORANGE
	3	RED
	2	BROWN
	1	BLACK

NOTES:

1. Use the color coded solder tabs on rotor and stator for each cooresponding signal. (refer to 1551-LY-901 for HSS wiring schematic through slip ring)
2. rotor connection: solder wires, seal in RTV, bundle signal cables with heat shrink tubing to align with the 3 radial holes at locations A, B and C.
3. stator connection: solder wires, seal in RTV, install right angle rubber boot w/ hose clamp.
4. install slip ring wire bundle assembly into HSS and secure slip ring rotor within shaft counter bore with machine screws (qty3).
5. apply 3 layers of protective coating around entire circumference at gauge locations A, B & C.
6. route stator wire bundle to gearbox exterior via unused HSS UW CRB RTD probe hole.
7. complete full bridge wiring with equal wire lengths as close as possible to gauges.

Slip Ring	Michigan Scientific
	SR20MW-T

Figure C-32. High-speed shaft slip ring. *Illustration by Romax Technology*

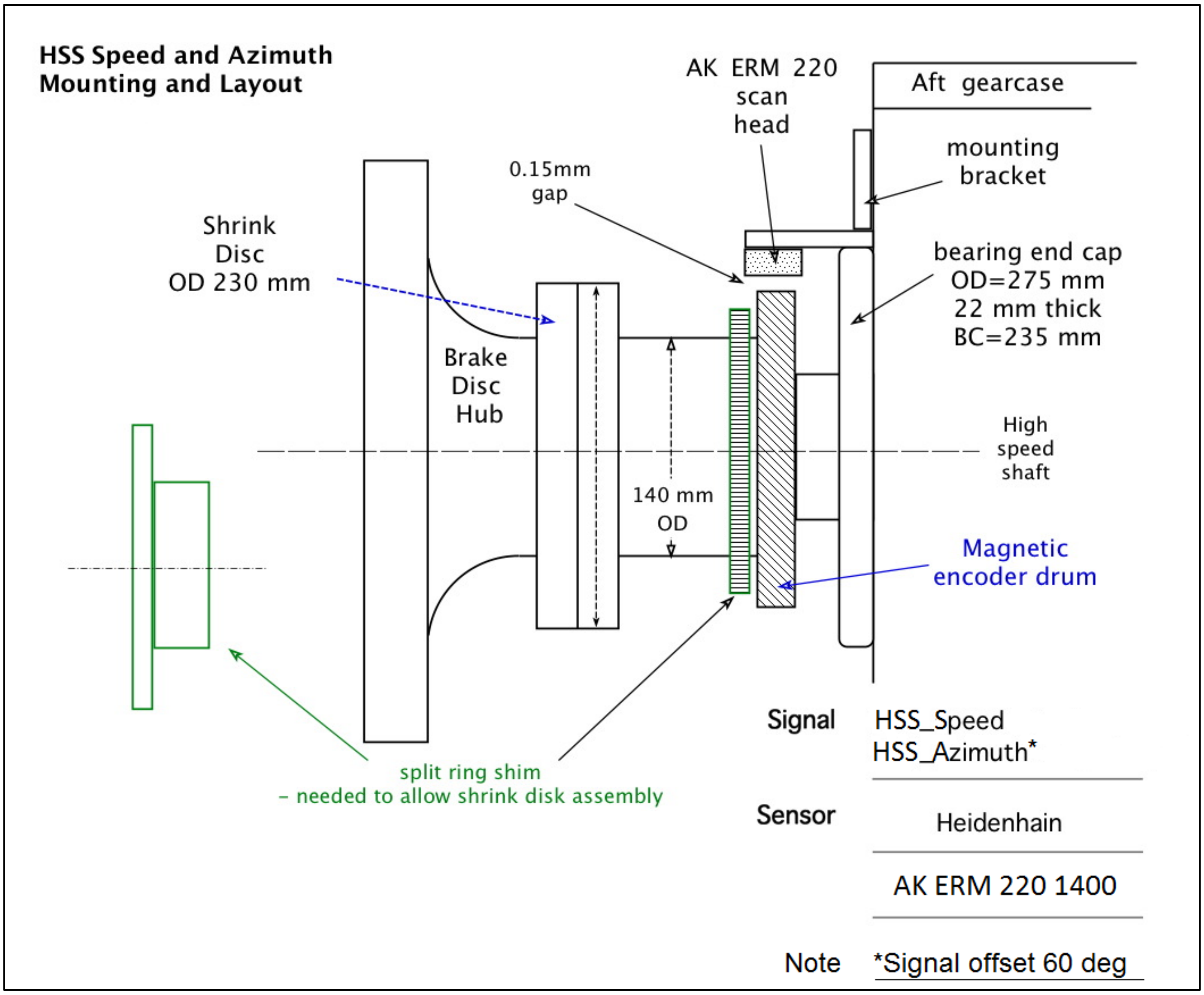


Figure C-33. High-speed shaft speed and azimuth. *Illustration by McNiff Light Industry*

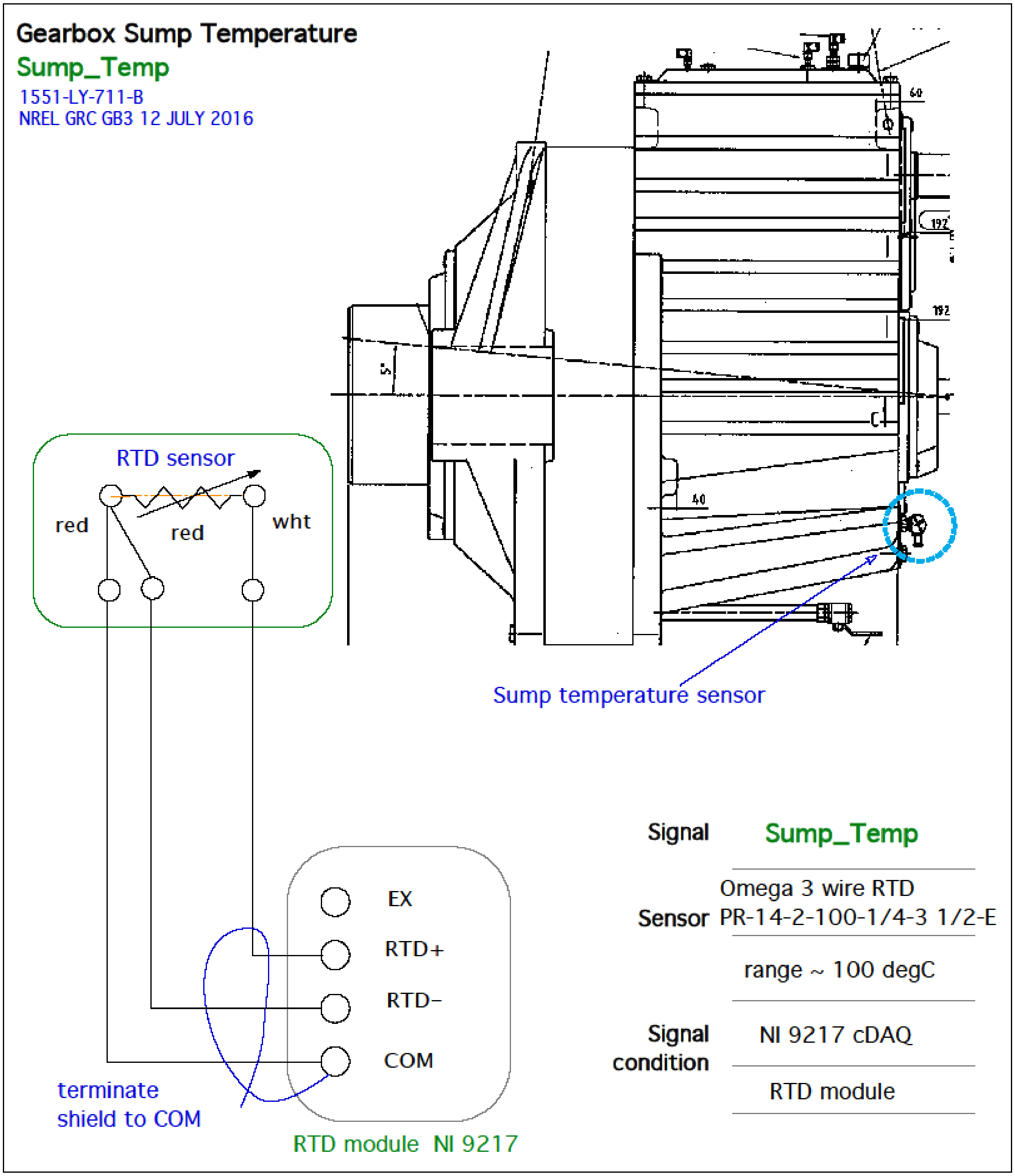


Figure C-34. Gearbox oil sump temperature. *Illustration by Romax Technology*