DATA PRODUCT SPECIFICATION FOR SEAFLOOR HIGH-RESOLUTION TILT

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Consortium for Ocean Leadership
1201 New York Ave NW, 4th Floor, Washington DC 20005
www.OceanLeadership.org

in Cooperation with

University of California, San Diego
University of Washington
Woods Hole Oceanographic Institution
Oregon State University
Scripps Institution of Oceanography
Rutgers University

Document Control Sheet

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This document has been reviewed and approved for release to Configuration Management.

OOI Senior Systems Engineer: 

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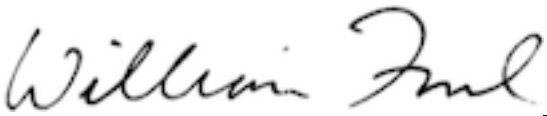
This document has been reviewed and meets the needs of the OOI Cyberinfrastructure for the purpose of coding and implementation.

OOI CI Signing Authority: 

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1 Abstract

This document describes the OOI Level 1 (L1) Seafloor High-Resolution Tilt (BOTTILT) core data product, derived from data output by the Applied Geomechanics LILY tilt sensor on board the Bottom Pressure Tilt (BOTPT) instruments on the Regional Scale Nodes (RSN) at Axial Seamount. This document is intended to be used by OOI programmers to construct appropriate processes to create the L1 BOTTILT core data product.

2 Introduction

2.1 Author Contact Information

Please contact Orest E. Kawka (kawkaoe@uw.edu) or the Data Product Specification lead (DPS@lists.oceanobservatories.org) for more information concerning the computation and other items in this document.

2.2 Metadata Information

2.2.1 Core Data Products

The following table summarizes the core data products that are produced by the processes described in this document:

Core Data Product Name	Level	Parameter	Descriptive Name	Core Data Product/Parameter Abstract (for Metadata)
BOTTILT	L0		Seafloor High-Resolution Tilt	The OOI Level 0 High-Resolution Seafloor Tilt (BOTTILT) core data product is produced by the BOTPT instrument class. The L0 core data product is derived directly from the Applied Geomechanics LILY Self-Leveling Borehole Tiltmeter sensor integrated in the BOTPT instrument. The resulting L0 BOTTILT core data product is composed of three parameters: Sensor X-Tilt, Y-Tilt (two orthogonal axes, in microradians, since the last re-leveling of the sensors), and Compass Direction (magnetic compass value, CCW from north; uncorrected for calibration offsets and magnetic declination).
		BOTTILT-XTLT	Sensor X-Tilt	The X-tilt magnitude (microradians) since the last re-leveling of the sensor is output by the high-resolution tiltmeter (LILY) on board the BOTPT instrument. Positive X-Tilt means the positive x-axis is in direction of downward tilt.
		BOTTILT-YTLT	Sensor Y-Tilt	The Y-tilt magnitude (microradians) since the last re-leveling of the sensor is output by the high-resolution tiltmeter (LILY) on board the BOTPT instrument. Positive Y-Tilt means the positive y-axis is in direction of downward tilt.

		BOTTILT-SCMP	Sensor Compass Direction	The sensor compass direction is output by the high-resolution tiltmeter (LILY) on board the BOTPT instrument and represents the heading of the negative y-axis direction of the tiltmeter measured in degrees CCW from north, uncorrected for calibration offsets and magnetic declination.
BOTTILT	L1		Seafloor High-Resolution Tilt	The OOI Level 1 Seafloor High-Resolution Tilt (BOTTILT) core data product is produced by the BOTPT instrument class. The data for the computation of this L1 core data product are derived from the Applied Geomechanics LILY Self-Leveling Borehole Tiltmeter sensor integrated in the BOTPT instrument. The resulting L1 BOTTILT core data product is composed of three resultant parameters, applicable since the last re-leveling of the sensor: Corrected compass direction of the positive Y-tilt axis (degrees, CW from north), Seafloor Tilt Magnitude (microradians), and Seafloor Tilt Direction (degrees, CW from north).
		BOTTILT-CCMP	Corrected Compass Direction	The compass direction of the positive Y-tilt axis (in degrees, CW from north) after corrections for calibration offsets and magnetic declination.
		BOTTILT-TMAG	Seafloor Tilt Magnitude	The magnitude (microradians) of the seafloor tilt, since the last re-leveling of the sensor, resulting from the L1 core data product computation.
		BOTTILT-TDIR	Seafloor Tilt Direction	The corrected direction (in degrees CW from North) of the seafloor downward tilt, since the last re-leveling of the sensor, resulting from the L1 core data product computation.

2.2.2 Auxiliary Data Products

The following table summarizes the auxiliary data products that are produced by the processes described in this document and may include engineering data about instruments and data produced directly by the instruments or derived herein which can be used for quality control of the core data products:

Auxiliary Data Product Name	Level	Parameter	Descriptive Name	Auxiliary Data Product/Parameter Abstract (for Metadata)
TLTTEMP	AUX		LILY Tiltmeter Temperature	The auxiliary data product Tiltmeter Temperature (TLTTEMP) is the temperature in °C internal to the Applied Geomechanics LILY Self-Leveling Borehole Tiltmeter sensor and is considered engineering data about this component of the BOTPT instrument which also has scientific value.
TLTVOLT	AUX		LILY Tiltmeter Voltage	The auxiliary data product Tiltmeter Voltage (TLTVOLT) is the voltage (volts) supplied to the Applied Geomechanics LILY Self-leveling Borehole Tiltmeter sensor and is considered engineering data about this component of the BOTPT instrument.
LRTTILT	AUX		IRIS Low-Resolution Tiltmeter Tilt	The auxiliary data product IRIS Low-Resolution Tilt (LRTTILT) is the tilt measured by the IRIS Low-Resolution Tiltmeter sensor on the BOTPT instrument. This data product consists of two parameters: x- and y-tilt (degrees).
		LRTTILT-XTLT	Sensor X-Tilt	The x-tilt direction (degrees) is output by the low-resolution tiltmeter (IRIS) on board the BOTPT instrument.
		LRTTILT-YTLT	Sensor Y-Tilt	The y-tilt direction (degrees) is output by the low-resolution tiltmeter (IRIS) on board the BOTPT instrument.
LRTTEMP	AUX		IRIS Low-Resolution Tiltmeter Temperature	The auxiliary data product IRIS Low-Resolution Tilt Temperature (LRTTEMP) is the temperature in °C internal to the IRIS Low-Resolution Tiltmeter sensor on the BOTPT instrument and is considered engineering data about this component of the BOTPT instrument which also has scientific value.
CRTTILT	AUX		Coarse-Resolution Tiltmeter Tilt	The auxiliary data product Coarse-Resolution Tilt (CRTTILT) is the tilt measured by the ADXL327 Coarse-Resolution Tiltmeter sensor integrated with the manual-leveling mechanism on the BOTPT instrument. This data product consists of two parameters: x- and y-tilt (integer degrees).
		CRTTILT-XTLT	Sensor X-Tilt	The x-tilt direction (integer degrees) is output by the coarse-resolution tiltmeter (ADXL327) on board the BOTPT instrument.
		CRTTILT-YTLT	Sensor Y-Tilt	The y-tilt direction (integer degrees) is output by the coarse-resolution tiltmeter (ADXL327) on board the BOTPT instrument.

CRTTEMP	AUX		Coarse-Resolution Tiltmeter Temperature	The auxiliary data product Coarse-Resolution Tiltmeter Temperature (CRTTEMP) is the temperature in integer °C internal to the coarse-resolution tiltmeter (ADXL327) sensor on the BOTPT instrument and is considered engineering data about this component of the BOTPT instrument which also has scientific value.

2.2.3 Computation Name

Not required for data products.

2.2.4 Computation Abstract (for Metadata)

The computation of the OOI Level 1 Seafloor High-Resolution Tilt (BOTTILT) core data product utilizes look-up tables for compass corrections and simple geometric calculations to derive the resultant corrected compass direction and seafloor tilt magnitude and direction (CW from north) from the X- and Y-tilt components and sensor compass reading data output by the Applied Geomechanics LILY Self-Leveling Borehole Tiltmeter sensor integrated in the BOTPT instrument. Note that the convention used here is that a positive tilt is the direction of downward tilt of the seafloor.

2.2.5 Instrument-Specific Metadata

See Section 4.4 for instrument-specific metadata fields that must be part of the output data.

2.2.6 Data Product Synonyms

Synonyms for this computation or data products thereby derived are the following, or a combination thereof:

- Tilt
- High-resolution tilt
- LILY tilt
- Seafloor tilt

2.2.7 Similar Data Products

Similar data products that these core data products may be confused with are the lower resolution (auxiliary data products) described herein and/or those derived from engineering (orientation) sensors on platforms or other instruments.

2.3 Instruments

For information on the instruments from which the L1 Seafloor High-Resolution Tilt (BOTTILT) core data product inputs are obtained, see the BOTPT Processing Flow document (DCN 1342-00060). This document contains information on the instrument class and make/models; it also describes the flow of data from the BOTPT instruments through all of the relevant QC, calibration, and data product computations and procedures.

Please see the Instrument Application in the SAF for specifics of instrument locations and platforms.

Details on the relationships between the three individual and different tiltmeter sensors onboard the BOTPT instrument is provided in Appendix E.

2.4 Literature and Reference Documents

The following are references with information about the three tilt sensors (LILY, IRIS, and

ADXL327) on board the BOTPT instruments. Only the LILY output is used to produce the L1 Seafloor High-Resolution Tilt (BOTTILT) core data product. Output from the IRIS and ADXL327 sensors are engineering data. Applied Geomechanics was the original manufacturer of both the LILY and IRIS tilt sensors and was subsequently acquired by the CARBO Ceramics company. The two sensors were procured from the latter company. Recently, most likely late 2012, Applied Geomechanics discontinued business operations and some assets were sold to Jewell Instruments (where the IRIS and LILY sensors are still available). Analog Devices is the manufacturer of the ADXL327.

These are the web sites for the manufacturer/vendor of the individual sensors:
http://www.carboceramics.com/appliedgeomechanics/
http://www.jewellinstruments.com/
http://www.analog.com/

This PDF document describes the LILY Self-Leveling Borehole Tiltmeter:
REFERENCE > Data Product Specification Artifacts > 1341-00060_BOTTILT > LILY_Borehole_Tiltmeter_L00259A_Description.pdf

This PDF document is the User Manual for the LILY Self-Leveling Borehole Tiltmeter:
REFERENCE > Data Product Specification Artifacts > 1341-00060_BOTTILT > LILY_Borehole_Tiltmeter_User_Manual.pdf

This PDF document describes the IRIS Tiltmeter (Tilt Switch & Controller):
REFERENCE > Data Product Specification Artifacts > 1341-00060_BOTTILT > IRIS_Tilt_Switch_Controller_Description.pdf

This PDF document is the User Manual for the IRIS Tiltmeter (Tilt Switch & Controller):
REFERENCE > Data Product Specification Artifacts > 1341-00060_BOTTILT > IRIS_Tilt_Switch_Controller_User_Manual.pdf

This PDF document describes the ADXL327 Coarse-Resolution Tilt Sensor (3-axis Accelerometer):
REFERENCE > Data Product Specification Artifacts > 1341-00060_BOTTILT > ADXL327_3-axis_Accelerometer_Description.pdf
(Information is also available at http://www.analog.com/en/mems-sensors/mems-inertial-sensors/adxl327/products/product.html)

2.5 Terminology

2.5.1 Definitions

The following terms are defined here for use throughout this document. Definitions of general OOI terminology are contained in the Level 2 Reference Module in the OOI requirements database (DOORS).

X-tilt = value measured by one of two orthogonal tilt sensors (microradians); a positive X-tilt value means the positive x-axis is in the direction of downward tilt

Y-tilt = value measured by one of two orthogonal tilt sensors (microradians); a positive Y-tilt value means the positive y-axis is in the direction of downward tilt

Resultant tilt magnitude = is the value (microradians) derived from the X-tilt and Y-tilt components as follows: Resultant tilt magnitude = SQRT $((\text{X-tilt})^2 + (\text{Y-tilt})^2)$

Sensor compass direction = value measured by the LILY compass sensor, which is the heading of the negative Y-tilt axis, measured CCW from north*, in degrees, for example:

Heading of negative Y-tilt axis	Heading of positive Y-tilt axis	Sensor Compass Direction
North	South	0
West	East	90
South	North	180
East	West	270

* Note: The L0 Sensor Compass Direction is uncorrected for calibration offsets and magnetic declination.

Corrected compass direction = azimuth of the positive Y-tilt axis, measured CW from north, in degrees, after corrections for calibration offsets and magnetic declination

Resultant tilt direction = azimuth of the Resultant tilt magnitude, in degrees, measured CW from north (calculated as described in the Appendix using the corrected compass direction)

2.5.2 Acronyms, Abbreviations and Notations

General OOI acronyms, abbreviations and notations are contained in the Level 2 Reference Module in the OOI requirements database (DOORS). The following acronyms and abbreviations are defined here for use throughout this document.

N/A

2.5.3 Variables and Symbols

The following variables and symbols are defined here for use throughout this document.

See Section 2.5.1 for variables and definitions thereof.

3 Theory

3.1 Description

The computations to produce the L1 BOTTILT core data product are simple geometric calculations manipulating the L0 BOTTILT core data products of sensor x- and y-tilt and compass values produced by the high-resolution tilt sensor component of the BOTPT instrument. The computational technique on board this Applied Geomechanics LILY Self-leveling Borehole Tiltmeter sensor is detailed in the manufacturer's literature as referenced in Section 2.4.

3.2 Mathematical Theory

See descriptions of the theoretical basis of computations onboard the Applied Geomechanics LILY Self-leveling Borehole Tiltmeter as detailed in the technical notes of the manufacturer's literature as referenced in Section 2.4 and on their website. The calculations to derive the resultant tilt magnitude and direction from the X- and Y-tilt components are based on simple vector geometry.

3.3 Known Theoretical Limitations

N/A

3.4 Revision History

No revisions to date.

4 Implementation

4.1 Overview

The raw data stream output by the BOTPT instrument contains data records for four (4) individual sensors. The specific data record tagged with a 4-character ID “LILY” is parsed to obtain the Level 0 BOTTILT core data product, which is then transformed into the Level 1 Seafloor High-Resolution Tilt (L1 BOTTILT) core data product using the computation described by this specification. The computation uses look-up tables to obtain sensor-specific corrected compass directions, and then a sequence of simple geometric calculations to derive the resultant high-resolution tilt magnitude and direction. See Appendix A.

4.2 Inputs

Inputs are:

- The data record in the raw data stream tagged with the 4-character ID “LILY”, followed by the comma delimiter, is used to create L0 and L1 core and auxiliary data products from the high-resolution LILY sensor.
- The data records in the raw data stream tagged with the 4-character ID’s “IRIS” and “HEAT”, both followed by the comma delimiter, are for engineering data and used to create the auxiliary data products associated with those sensors. See Appendix D.

Input Data Formats:
The BOTPT instrument outputs data records in a single line of ASCII text that is comma delimited and ends with a line feed (\n). The data fields of interest (other than Date/Time and Serial Number) are floating point numbers. **The number of digits displayed are the *significant digits,* except for the sensor compass value, which should be rounded to the nearest integer (degrees).**

For the L0 core data product, the (uncorrected) sensor compass value, parsed from the raw data stream, is the azimuth of the negative Y-tilt direction. This is opposite of the off-the-shelf LILY tiltmeter in which the compass heading is the positive Y direction. For the OOI BOTPT instruments, the magnetic compass is mounted rotated 180 degrees relative to the tilt sensors for space reasons. The L0 sensor compass value is also not corrected for calibration offsets and magnetic declination (the magnetic declination correction is set to zero onboard the instrument). These corrections are made in the steps to create the L1 data products.

The convention used for the L1 core data products is that a positive tilt is the direction of downward tilt of the seafloor.

The LILY sensor outputs data records in a single line of ASCII text that is comma delimited. The sensor will operate at 1 Hz, and each record will have its own ID tag and time stamp. There will be four different ID tags from the BOTPT instruments to differentiate data output from the four onboard sensors. The four ID tags will be: NANO, LILY, IRIS, HEAT.

All data records with the LILY ID tag are processed for the L0 and L1 BOTTILT data products.

The format of the LILY tilt data records will be as follows:

```
LILY,2012/03/22 12:34:56,-330.000,-330.000,263.33,21.11,11.87,N7055
  |                |              |         |       |      |      |
  |                |              |         |       |      |     S/N
  |                |              |         |       |      Voltage
  |                |              |         |       Temp. (degrees C)
  |                |              |         Compass (degrees)
  |                |              Y-tilt (microradians)
  |                X-tilt (microradians)
  |             Date/Time (YYYY/MM/DD HH:MM:SS)
 ID tag (LILY=LILY high-resolution tiltmeter)
```

The sensor x-tilt, y-tilt, and compass fields are extracted to create the Level 0 core data products for the Seafloor High-Resolution Tilt (BOTTILT), and they are also subsequently transformed as described herein to form the L1 BOTTILT core data products.

The tiltmeter has a maximum range of ± 330 microradians, so when the X-tilt or Y-tilt values exceed ± 300, a command will need to be sent automatically by CI to the instrument to re-level the sensors (which takes a few minutes). Thus, there will be offsets in the LILY tilt data if and when either of the X-tilt or Y-tilt values exceeds ±300, because the sensor will be re-leveled and, afterward, the X-tilt and Y-tilt values will both be near zero. No special correction for these offsets is required as part of the L1 Seafloor High-Resolution Tilt (L1 BOTTILT) core data product. The compass and tilt values are used to determine the resultant tilt magnitude and direction since the last re-leveling of the sensor, as explained below in Appendix A.

The Date/Time field is primary and required for follow-on data processing and must be stored/ associated with the core and auxiliary data products above.

The temperature and supply voltage are considered engineering data, and while they are not used directly in the production of the core data product, they are identified and captured as **Auxiliary Data Products** in this document.

The LILY tilt sensor serial numbers (S/N above) are used to identify the proper column of the look-up table and need to be captured as metadata attributes for quality assurance procedures.

Note that valid data records will need to be distinguished from non-data records output from the LILY tilt sensor (for example, start-up strings, echoed commands and output during re-leveling). All non-data records will have an asterisk (*) after date/time stamp, as follows:

```
LILY,2012/03/22 12:34:56,*9900XYC2
```

Any record with an asterisk (*) in this position should be separated from the valid LILY data records and recorded to a separate metadata output file. ***They need to be captured as metadata attributes/resource file.***

All data records with the IRIS or HEAT ID tags are engineering data and should be parsed as described in Appendix D. The fields extracted from the IRIS and HEAT data records are used to create the auxiliary data products: Low-Resolution Tilt (LRTTILT) and Coarse-Resolution Tilt (CRTTILT).

4.3 Processing Flow

The specific steps necessary to create all calibrated and quality controlled data products for BOTPT core instrument are described in the instrument-specific Processing Flow documents (DCN 1342-00060). These processing flow documents contain flow diagrams detailing all of the

specific procedures (data product and QC) necessary to compute all levels of data products from the instrument and the order of these procedures.

4.3.1 L0 and L1 BOTTILT core data products and TLTTEMP and TLTVOLT auxiliary data products

The processing flow for the production of the L0 and L1 BOTTILT core data products and auxiliary data products (TLTTEMP and TLTVOLT) is:

Step 1:
Parse the raw data stream and identify the appropriate data record (tagged as LILY and without * after the date/time field).

Step 2:
The following operations are performed on the LILY data record:

- Extract the Date/Time field and associate this with the core and auxiliary data products described here.
- Extract the x-tilt, y-tilt, and sensor compass fields to produce the L0 BOTTILT core data product (3 separate components).
- Extract the temp field to produce the TLTTEMP auxiliary data product.
- Extract the voltage field to produce the TLTVOLT auxiliary data product.
- Read LILY serial number to be used in the sensor-specific L1 compass direction correction

Step 3: Transform the x-tilt, y-tilt, and sensor compass fields into the L1 BOTTILT core data products (Corrected Compass Direction, Seafloor Tilt Magnitude and Seafloor Tilt Direction) using the steps as described in Appendix A. The Corrected Compass Direction will be determined from sensor-specific look-up tables that include corrections (based on LILY serial number) for calibration offsets and for magnetic declination (see Appendix B).

Step 4:
Store the extracted L0 and L1 core and auxiliary data products and associate them with the Date/Time field extracted above.

4.3.2 LRTTILT, LRTTEMP, CRTTILT, and CRTTEMP Auxiliary data products

The processing flows for the production of the auxiliary data products (LRTTILT, LRTTEMP, CRTTILT, CRTTEMP) from the engineering tiltmeter sensors IRIS and ADXL327 are:

Step 1:
Parse the raw data stream and identify the appropriate records (tagged as IRIS and HEAT).

Step 2:
The following operations are performed on the corresponding IRIS and HEAT data records:

- Extract the Date/Time field and associate this with the auxiliary data products described here.
- Extract the x-tilt, y-tilt, and temperature from the IRIS data record to produce the LRTTILT (2 separate parameters) and LRTTEMP auxiliary data products.
- Extract the x-tilt, y-tilt, and temperature from the HEAT data record to produce the CRTTILT (2 separate parameters) and CRTTEMP auxiliary data products.

Step 3:
Store the extracted auxiliary data products and associate them with the Date/Time fields extracted above.

4.4 Outputs

The outputs of the Seafloor High-Resolution Tilt core data product computations are:

- L0 BOTTILT-XTLT, parameter Sensor X-tilt [microradians]
- L0 BOTTILT-YTLT, parameter Sensor Y-tilt [microradians]
- L0 BOTTILT-SCMP, parameter Sensor Compass Direction [degrees]
- L1 BOTTILT-CCMP, parameter Corrected Compass Direction [integer degrees]
- L1 BOTTILT-TMAG, parameter Resultant Tilt Magnitude [microradians]
- L1 BOTTILT-TDIR, parameter Resultant Tilt Direction [integer degrees]

The auxiliary data products output from of the LILY high-resolution tiltmeter are:

- TLTTEMP, High-resolution tiltmeter Temperature [°C]
- TLTVOLT, High-resolution tiltmeter Voltage [volts]

The number of digits in the input values are to be retained as the number of significant digits for all of the output values, except for the L1 BOTTILT-CCMP and L1 BOTTILT-TDIR. That output is only significant to integer degrees, due to the form of the compass correction.

The convention for resultant L1 Seafloor Tilt Direction used here is toward downward tilt of the seafloor.

The metadata that must be associated with the above data products are:

- Date/Time as recorded in the Date/Time stamp in the “LILY” raw data record (see Section 4.2 for source and format) with time precision of integer seconds.

Engineering tiltmeter sensor outputs:

The auxiliary data products output from the IRIS Low-resolution Tiltmeter (see Appendix D) are:

- LRTTILT-XTLT, parameter sensor X-tilt [degrees]
- LRTTILT-YTLT, parameter sensor Y-tilt [degrees]
- LRTTEMP, Low-resolution tiltmeter temperature [degrees C]

The auxiliary data products output from the ADXL327 Coarse-Resolution Tiltmeter (see Appendix D) are:

- CRTTILT-XTLT, parameter X-tilt [integer degrees]
- CRTTILT-YTLT, parameter Y-tilt [integer degrees]
- CRTTEMP, Coarse-resolution tiltmeter temperature [integer degrees, C]

The metadata that must be associated with the above data products are:

- Date/Time as recorded in the IRIS and HEAT raw data records (see Appendix D)

See Appendix B for a discussion of the accuracy of the output for the core data products.

4.5 Computational and Numerical Considerations

4.5.1 Numerical Programming Considerations

There are no numerical programming considerations for this computation. No special numerical methods are used.

4.5.2 Computational Requirements

- The LILY High-Resolution Tiltmeter sensor of the BOTPT instrument will operate nominally at 1 Hz, so there would be one (1) such output record per second, each with its own date/time stamp.

4.6 Code Verification and Test Data Set

A test data set composed of a full suite of the different types of data records (sensor-specific) produced by the BOTPT instrument along with the expected outputs of this DPS is provided in this directory: REFERENCE > Data Product Specification Artifacts > 1341-00060_BOTTILT

The README file in the linked directory provides additional information on the files included.

Appendix A Example Code

Here are the steps for processing the L0 BOTTILT core data product and creating the L1 BOTTILT core data product.

1) Read in a LILY data record.
2) If the record contains a "*" after the time-stamp, signifying a non-data record, record it to a separate metadata file, but skip it for this data product and go back to step 1; otherwise, move on to step 3.
3) Retrieve the Date, Time, X-Tilt, Y-Tilt, & Sensor Compass Direction values from the record.
4) Round the Sensor Compass Direction to the nearest integer.
5) Using a sensor-specific look-up table (based on LILY serial number; see Appendix B), retrieve the Corrected Compass Direction, which includes corrections for changing from direction of the negative Y-tilt axis to the positive Y-tilt axis, from CCW to CW azimuth from north, calibration offsets, and magnetic declination for Axial Seamount of 17 degrees east of north.
6) Compute the Resultant Tilt Magnitude value as the square-root of (X-Tilt^2 + Y-Tilt^2). Thus, this value is always positive.
7) Send the X-Tilt, Y-Tilt, & Corrected Compass Direction to the COMPASS SUBROUTINE (see below) for computing the Resultant Tilt Direction value.
8) Write to the L1 BOTTILT data product file:
Date; Time; Corrected Compass Direction (parameter CCMP), Seafloor Tilt Magnitude (parameter TMAG), and Seafloor Tilt Direction (parameter TDIR).
9) Go back to step 1.

COMPASS SUBROUTINE (CS)
This subroutine computes the Resultant Tilt Direction using the X-Tilt Y-Tilt, and the Corrected Compass Direction (CCMP):
CS1) Compute an ANGLE using one of the following cases:
        If X-Tilt = 0 and Y-Tilt > 0, then ANGLE = +90
        If X-Tilt = 0 and Y-Tilt < 0, then ANGLE = -90
        If Y-Tilt = 0, then ANGLE = 0
        else ANGLE = arctan(Y-Tilt/X-Tilt)
CS2) Then compute the Resultant Tilt Direction as follows:
        If X-Tilt > 0 or X-Tilt=0, then
          Resultant Tilt Direction = 90 - ANGLE + CCMP
        Else If X-Tilt < 0, then
          Resultant Tilt Direction = 270 - ANGLE + CCMP
CS3) Apply Modulus 360 to the Resultant Tilt Direction so that it will be between 0-360
        e.g. if Resultant Tilt Direction = 450, it will become 90.
CS4) Return the Resultant Tilt Direction value to the main program.

A similar method to the one above was used to process LILY tilt data from a prototype BOTPT instrument tested on the MARS cable with the data displayed on this web site:
http://www.pmel.noaa.gov/vents/geology/mars/

Appendix B Look-up Table for LILY Compass Corrections

The following table should be used for making the sensor-specific compass corrections, based on the LILY serial number (S/N). SCMP is the input Sensor Compass Direction (L0, as output by the LILY sensor). The CCMP is the Corrected Compass Direction to be used in the L1 data product.

SCMP	CCMP				
	S/N=9651	S/N=9655	S/N=9676	S/N=9652	S/N=9656
0	183	173	200	173	166
1	182	173	199	172	165
2	182	172	198	171	164
3	182	172	197	170	164
4	182	172	196	170	163
5	182	171	195	169	162
6	182	171	194	168	162
7	182	171	193	168	161
8	182	171	192	167	161
9	182	170	191	166	160
10	181	170	191	166	159
11	181	170	190	165	159
12	181	169	189	164	158
13	181	169	188	164	157
14	181	169	187	163	157
15	181	168	186	163	156
16	181	168	185	162	156
17	181	168	184	161	155
18	180	168	183	161	155
19	180	167	182	160	154
20	180	167	181	160	154
21	180	167	180	159	153
22	180	166	179	159	153
23	180	166	178	158	152
24	180	166	177	157	151
25	180	166	176	157	151
26	179	165	175	156	150
27	179	165	174	156	150
28	179	165	173	155	149
29	179	165	172	155	149
30	179	164	171	154	148
31	179	164	171	154	148
32	179	164	170	153	147
33	179	163	169	153	147
34	178	163	168	152	146
35	178	163	167	151	146
36	178	163	166	151	146
37	178	162	165	150	145

38	178	162	164	150	145
39	178	162	163	149	144
40	178	162	162	149	144
41	178	161	161	148	143
42	177	161	161	148	143
43	177	161	160	147	142
44	177	161	159	147	142
45	177	160	158	146	142
46	177	160	157	146	141
47	177	160	156	145	141
48	176	160	155	145	140
49	176	159	154	144	140
50	176	159	153	144	139
51	176	159	152	143	139
52	175	158	151	143	139
53	175	158	151	142	138
54	175	158	150	142	138
55	175	158	149	141	137
56	174	157	148	141	137
57	174	157	147	140	136
58	174	157	146	140	136
59	174	157	145	139	136
60	173	156	144	139	135
61	173	156	143	138	135
62	173	156	142	138	134
63	173	155	141	137	134
64	172	155	140	137	133
65	172	154	139	136	133
66	172	154	138	136	132
67	172	154	137	135	132
68	171	153	136	135	132
69	171	153	135	134	131
70	171	153	134	134	131
71	171	152	133	133	130
72	170	152	132	133	130
73	170	152	131	132	129
74	170	151	130	131	129
75	170	151	129	131	129
76	169	151	128	130	128
77	169	150	127	130	128
78	169	150	126	129	127
79	169	149	125	129	127
80	168	149	124	128	126
81	168	149	123	128	126
82	168	148	122	127	125
83	168	148	121	127	125
84	167	148	120	126	124

85	167	147	119	126	124
86	167	147	118	125	123
87	166	146	117	124	123
88	165	146	116	124	122
89	165	145	115	123	122
90	164	145	114	123	122
91	163	144	113	122	121
92	163	144	111	121	121
93	162	143	110	121	120
94	161	143	109	120	120
95	160	142	108	120	119
96	160	141	107	119	119
97	159	141	106	119	118
98	158	140	105	118	118
99	158	140	104	117	117
100	157	139	103	117	117
101	156	139	102	116	116
102	155	138	101	115	116
103	154	138	100	115	115
104	153	137	99	114	115
105	152	137	98	113	114
106	151	136	97	113	113
107	150	135	96	112	113
108	149	135	95	111	112
109	148	134	94	111	112
110	147	133	93	110	111
111	146	132	91	109	111
112	144	131	90	109	110
113	143	131	89	108	110
114	141	130	88	107	109
115	140	129	87	107	108
116	139	128	86	106	108
117	137	128	85	105	107
118	136	127	84	105	107
119	134	126	83	104	106
120	133	125	81	103	105
121	131	124	80	102	105
122	130	123	79	101	104
123	129	122	78	101	103
124	127	121	77	100	103
125	125	120	76	99	102
126	124	119	75	98	101
127	122	118	74	98	100
128	121	117	73	97	100
129	119	116	71	96	99
130	117	115	70	95	98
131	116	114	69	94	98

132	114	113	68	93	97
133	112	111	67	92	96
134	111	110	66	91	95
135	108	109	64	91	94
136	107	108	63	90	94
137	105	107	61	89	93
138	103	106	60	88	92
139	101	105	59	87	91
140	99	103	57	86	90
141	97	102	56	85	89
142	96	101	55	84	89
143	94	100	54	83	88
144	92	98	53	82	87
145	91	97	52	81	86
146	89	96	51	80	85
147	87	94	50	79	84
148	85	93	49	78	83
149	83	91	48	77	82
150	81	90	47	76	81
151	79	89	46	75	80
152	77	87	45	74	79
153	75	86	44	73	78
154	73	84	43	71	77
155	71	82	41	70	76
156	69	81	40	69	75
157	67	79	39	68	74
158	66	77	38	67	73
159	64	76	37	66	71
160	62	74	36	65	70
161	61	72	35	63	69
162	59	71	33	62	68
163	57	70	32	61	67
164	55	69	31	60	66
165	53	67	30	58	65
166	51	66	28	57	63
167	49	64	27	56	62
168	47	62	26	55	61
169	45	61	25	53	60
170	43	59	24	52	58
171	41	57	23	51	57
172	39	56	21	50	56
173	37	54	20	48	54
174	35	52	19	47	53
175	33	51	18	46	51
176	31	49	17	44	50
177	29	47	16	43	49
178	27	45	15	41	47

179	26	43	14	40	46
180	24	41	13	39	45
181	22	39	11	37	43
182	21	37	10	36	42
183	19	36	9	35	41
184	17	34	8	33	40
185	15	32	7	32	38
186	13	31	6	31	37
187	11	29	5	30	36
188	9	27	3	28	34
189	7	26	2	27	32
190	5	24	1	26	31
191	3	22	0	24	29
192	1	21	358	23	27
193	359	19	357	21	26
194	357	17	356	20	24
195	356	15	355	19	23
196	354	13	354	17	21
197	352	11	353	16	20
198	351	9	351	14	19
199	349	7	350	13	17
200	347	6	349	11	16
201	345	4	348	10	14
202	343	2	347	9	13
203	341	1	346	7	11
204	339	359	345	6	10
205	337	357	344	4	9
206	335	356	343	2	7
207	333	354	341	1	6
208	331	352	340	359	4
209	329	350	339	357	2
210	327	349	338	356	1
211	326	347	337	354	359
212	324	345	336	353	357
213	322	343	335	351	356
214	321	340	334	350	354
215	319	339	333	349	352
216	317	337	332	347	351
217	315	336	331	346	349
218	313	334	330	344	347
219	311	332	329	343	346
220	309	331	328	341	344
221	307	329	327	340	343
222	306	327	326	339	341
223	304	326	325	337	340
224	302	324	324	336	339
225	301	322	323	334	337

226	299	321	321	332	336
227	297	319	320	331	334
228	295	317	319	329	332
229	293	315	318	327	331
230	291	313	317	326	329
231	289	311	316	324	327
232	287	309	315	323	326
233	286	307	314	321	324
234	284	306	313	320	322
235	282	304	312	319	321
236	281	302	311	317	319
237	279	301	311	316	317
238	277	299	310	314	316
239	276	297	309	313	314
240	274	296	308	311	312
241	272	294	307	310	311
242	271	292	306	309	309
243	269	291	305	307	307
244	267	289	304	306	306
245	265	287	303	304	304
246	263	286	302	302	303
247	261	284	301	301	301
248	259	282	300	299	300
249	257	281	299	297	299
250	256	279	298	296	297
251	254	277	297	294	296
252	252	276	296	293	294
253	251	274	295	291	292
254	249	272	294	290	291
255	247	271	293	289	289
256	246	269	292	287	287
257	244	267	291	286	286
258	243	266	290	284	284
259	241	264	289	283	283
260	240	263	288	281	281
261	239	261	287	280	280
262	237	260	286	279	279
263	236	259	285	277	277
264	234	257	284	276	276
265	232	256	283	274	274
266	231	254	282	273	272
267	229	252	281	271	271
268	227	251	281	270	269
269	226	249	280	269	267
270	224	247	279	267	266
271	223	246	278	266	264
272	221	244	277	264	263

273	220	243	276	263	261
274	219	241	275	261	260
275	217	240	274	260	259
276	216	239	273	259	257
277	215	237	272	257	256
278	214	236	271	256	254
279	213	234	271	255	253
280	211	233	270	253	251
281	210	231	269	252	250
282	209	230	268	251	249
283	208	229	267	250	247
284	207	227	266	248	246
285	206	226	265	247	244
286	205	225	264	246	243
287	204	223	264	245	241
288	204	222	263	243	240
289	203	221	262	242	239
290	202	220	261	241	237
291	201	218	260	240	236
292	200	217	259	238	235
293	199	216	259	237	233
294	199	215	258	236	232
295	198	214	257	235	231
296	197	213	256	233	230
297	197	211	255	232	228
298	196	210	254	231	227
299	196	209	253	230	226
300	196	208	252	228	225
301	195	207	251	227	223
302	195	206	251	226	222
303	195	205	250	225	221
304	194	204	249	224	220
305	194	203	248	223	218
306	194	202	247	221	217
307	193	201	246	220	216
308	193	201	245	219	215
309	192	200	244	218	213
310	192	199	243	217	212
311	192	198	242	216	211
312	191	197	241	215	210
313	191	196	241	214	208
314	191	195	240	213	207
315	190	195	239	211	206
316	190	194	238	210	205
317	190	193	237	209	204
318	189	193	236	208	203
319	189	192	235	207	201

320	189	191	234	206	200
321	188	191	234	205	199
322	188	190	233	204	198
323	188	189	232	203	197
324	187	189	231	202	196
325	187	188	230	201	195
326	187	187	229	200	194
327	187	187	229	199	193
328	187	186	228	198	192
329	186	186	227	197	191
330	186	185	226	196	190
331	186	185	225	195	189
332	186	184	224	194	188
333	186	184	223	194	187
334	186	183	222	193	186
335	186	183	221	192	185
336	186	182	221	191	184
337	185	182	220	190	183
338	185	181	219	189	182
339	185	181	218	189	181
340	185	180	217	188	181
341	185	180	216	187	180
342	185	179	215	186	179
343	185	179	214	185	178
344	185	178	214	185	177
345	184	178	213	184	176
346	184	177	212	183	175
347	184	177	211	182	175
348	184	177	210	181	174
349	184	176	209	181	173
350	184	176	209	180	173
351	184	176	208	179	172
352	184	175	207	178	171
353	183	175	206	178	170
354	183	175	205	177	170
355	183	175	204	176	169
356	183	174	203	175	168
357	183	174	202	175	168
358	183	174	201	174	167
359	183	173	201	173	166
360	183	173	200	173	166

Appendix C Output Accuracy

The nominal resolution of the LILY high-resolution tiltmeter is 5 nanoradians according to the manufacturer (see documentation referenced in Section 2.4). The effective accuracy, precision, and resolution of the tilt measurements on the seafloor will be a function of many factors that are difficult to quantify (stiffness of the instrument frame, stability of the frame on the seafloor, etc.). The resolution of the Resultant Tilt Magnitude should be better than 1 microradian and the resolution of the Resultant Tilt Direction should be 1 degree. The L1 Seafloor High-Resolution Tilt data product algorithm has the same accuracy, precision, resolution as the LILY tilt sensor itself.

The DOORS resolution requirement for the tilt measurement by the BOTPT instrument is 5 nanoradians (Requirement L4-RSN-IP-RQ-167, Baseline Version 2.2.3, NSF-CCB-2012-07-03).

The DOORS precision requirement for the tilt measurement by the BOTPT instrument is 5 nanoradians (Requirement L4-RSN-IP-RQ-626, Baseline Version 2.2.3, NSF-CCB-2012-07-03).

Appendix D Sensor Calibration Effects

See the manual for the LILY tiltmeter:
REFERENCE > Data Product Specification Artifacts > 1341-00060_BOTTILT > LILY_Borehole_Tiltmeter_User_Manual.pdf

The components of the LILY high-resolution tilt sensor, consisting of X-tilt, Y-tilt, and magnetic compass sensors are physically repackaged in the BOTPT instruments (as compared to an “off-the-shelf” instrument) for space reasons. Therefore, it is necessary to calibrate the LILY sensor compass direction output for each LILY sensor by comparing it to measured orientations in the field. This was done at a compass calibration stand at NOAA/PMEL in Seattle, WA, with each of the BOTPT instruments. The measured instrument orientations were compared with the sensor compass direction values for each of the five LILY sensors to construct the compass correction look-up table in Appendix B.

Appendix E Data Formats for the BOTPT Tilt Engineering Data

There are 4 data streams from individual sensors on the BOTPT instruments that are distinguished by a 4-character ID tag at the beginning of each output record that is transmitted to shore. The 4 ID tags are as follows:

```
1) NANO – for the Nano-resolution bottom pressure sensor (40 Hz)
2) LILY – for the LILY high-resolution tilt sensor (1 Hz)
3) IRIS – for the IRIS low-resolution tilt sensor (1 Hz)
4) HEAT – for the ADXL327 coarse-resolution tilt sensor (2-3 Hz)
```

All data records with the NANO ID tag are processed for the L1 BOTPRES data product (see DCN 1341-00070).

All data records with the LILY ID tag are processed for the L0 and L1 BOTTILT data product (as described in this DPS).

All raw data records with the IRIS or HEAT ID tags are from engineering tiltmeter sensors integrated in the BOTTILT instrument and should also be processed. Specific fields of these data records are extracted and stored as named auxiliary data products. The processing of the IRIS and HEAT raw data records is also included in this DPS and their data formats are described in this Appendix. Information about the sensors themselves is included in Section 2.4 above.

The IRIS data format will be as follows:

```
IRIS,2012/03/22 12:34:56, -00.619,000.023,018.910,N2212
  |           |              |       |       |      |
  |           |              |       |       |      Serial number
  |           |              |       |       Temperature (degrees C)
  |           |              |       Y-tilt value (degrees)
  |           |              X-tilt value (degrees)
  |           Date/Time (YYYY/MM/DD HH:MM:SS)
  ID tag (IRIS=IRIS low-resolution tiltmeter)
```

```
Any commands sent to the instrument are echoed.  Such non-data records
will be distinguished from valid data by an asterisk (*) after the
time-stamp, as follows (the same protocol as for the LILY tilt sensor):

IRIS,2012/03/22 12:34:56,*9900XYC2

It is suggested that valid data records and non-data records should be
separated and stored in separate files.
```

The HEAT data format (from the AADXL327 coarse-resolution tilt sensor) will be as follows:

```
HEAT,2012/03/22 12:34:56,0002,0001,0018
  |           |             |    |    |
  |           |             |    |    Temperature (integer degrees C)
  |           |             |    Y-tilt value (integer degrees)
  |           |             X-tilt value (integer degrees)
  |           Date/Time (YYYY/MM/DD HH:MM:SS)
  ID tag (HEAT=coarse-resolution tilt sensor for LILY heater)
```

The ADXL327 coarse tilt sensor does not accept commands, but any heater on/off commands will be echoed in a similar way to shown above (with an asterisk after the date-time stamp):

```
HEAT,2012/03/22 12:34:56,*5
```

Additional details on the relationships between the various tiltmeter sensors onboard the BOTPT instrument are provided in Appendix E.

Appendix F Tiltmeter Sensors on the BOTPT Instrument

Clarification of the three different tiltmeter sensors onboard the BOTPT instrument, their locations, and their roles is provided in this Appendix.

There are three tiltmeter sensors onboard the BOTPT instrument with all of the x- and y-tilt axes aligned:

1) The Applied Geomechanics LILY Self-Leveling Borehole Tiltmeter is the primary tilt sensor for science and creation of the L0 and L1 BOTTILT core data products. This high-resolution sensor is positioned inside three nested cylindrical housings: (a) the inner LILY tilt sensor housing, (b) the middle gimbal housing, and (c) the outer pressure housing. The LILY tilt sensor housing is held in a gimbaled mount inside the gimbal housing, which is partially filled with jojoba oil that has a freezing/melting point at about 8 °C and so holds the tilt sensor housing firmly in place at normal seafloor temperature (~ 3 °C). The gimbal housing has a heater on its base to enable the jojoba oil to be melted on command from shore to allow the tilt sensor housing to re-orient in the gimbal assembly (by gravity) and increase the dynamic range of the LILY tilt measurements (in case the instrument frame cannot be leveled well during deployment on the irregular seafloor surface). The LILY has a limited measurement range (± 330 microradians), but it can re-level itself on command to increase that range to ± 10 degrees. The gimbal assembly increases that dynamic range by another ± 15 degrees. NOTE: The LILY compass is mounted to the back of the strong-back that the LILY tilt sensors are mounted on, but the compass does not move when the x- and y-tilt axes are leveled.

The following low- and coarse-resolution tiltmeter sensors are included in the BOTPT instrument in order to know the orientation in space of the LILY sensors and their housings, to make sure they are oriented within the sensor's dynamic range limits, and to give important engineering information during deployment and at other times when the heater is turned on/off and the gimbal assembly reorients itself.

2) The IRIS Low-Resolution Tiltmeter sensor is located on top of the gimbal housing. Thus, it provides the orientation of the gimbal housing itself, not the LILY tiltmeter sensor inside. This will be important information when positioning the instrument during deployment.

3) The Coarse-Resolution Tiltmeter (ADXL327) sensor is located on the same strong-back that the LILY high-resolution sensors are on, but has a much larger dynamic range and much lower resolution. Thus, it gives the orientation of the LILY tilt sensors in a larger context.

These sensors will record what happens when the heater is turned on/off and the LILY tilt housing re-orients itself inside the gimbal housing. The temperature sensors and the associated temperature auxiliary data products will confirm the response of the heater.