Earth and Space Science

Supporting Information for

The Self-Calibrating Tilt Accelerometer: A method for observing tilt and correcting drift with a triaxial accelerometer

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Text S1. Anomalous Calibrations at Axial Seamount

A total of 43 anomalous calibrations were identified throughout the Axial Seamount SCTA deployment: 26 at Location 1 and 17 at Location 2. As an example, the acceleration data for 5 good calibrations and one anomalous calibration in the +X1 orientation at Location 1 are shown in Figure S3. The primary indication of a anomalous calibration is that the total acceleration, a_T, lies well outside the normal bounds. Usually, most of the anomalous contribution to a_T arises from the Z channel with other channels contributing smaller amounts. When anomalous calibrations occur, they can be seen on one or several calibrations within a sequence and in only one instance comprised all the calibrations in a sequence. Anomalous calibrations are sometimes accompanied by higher noise levels on some channels (Figure S3b). We do not understand the cause of anomalous calibrations. They are most likely a mechanical problem but have been unable to reproduce them after recovering the SCTA from Axial because the accelerometer performed normally during a post-experiment factory recalibration – most of the anomalous calibrations occurred early on. Because the anomalous calibrations are readily identifiable from the offset in a_T, they are easily removed prior to characterizing and correcting sensor drift by inspecting plots of the calibrations against time (Figures S4 and S5).

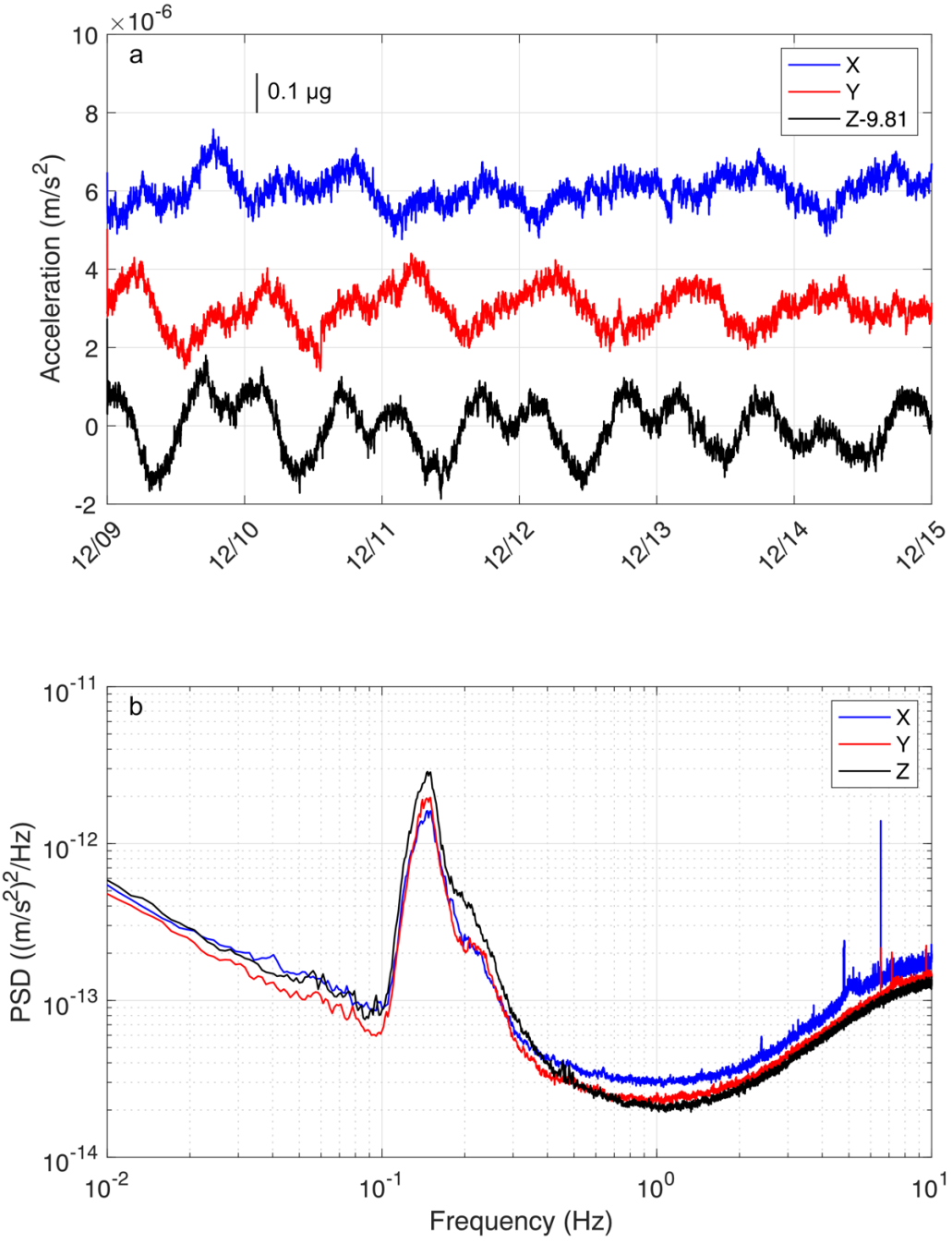

Figure S1. (a) Representative 6-days of data from Piñon Flab Observatory with the SCTA in the measurement orientation (with the Z channel in the vertical) starting 12/09/2018. X, Y, and Z channel observations are plotted in blue, red, and black, respectively, after removing the mean and linear trend and decimating to 1 sample/minute. Vertical offsets are for display purposes only. (b) Associated power spectral density for the three channels, calculated without decimating the data and plotted with the same colors.

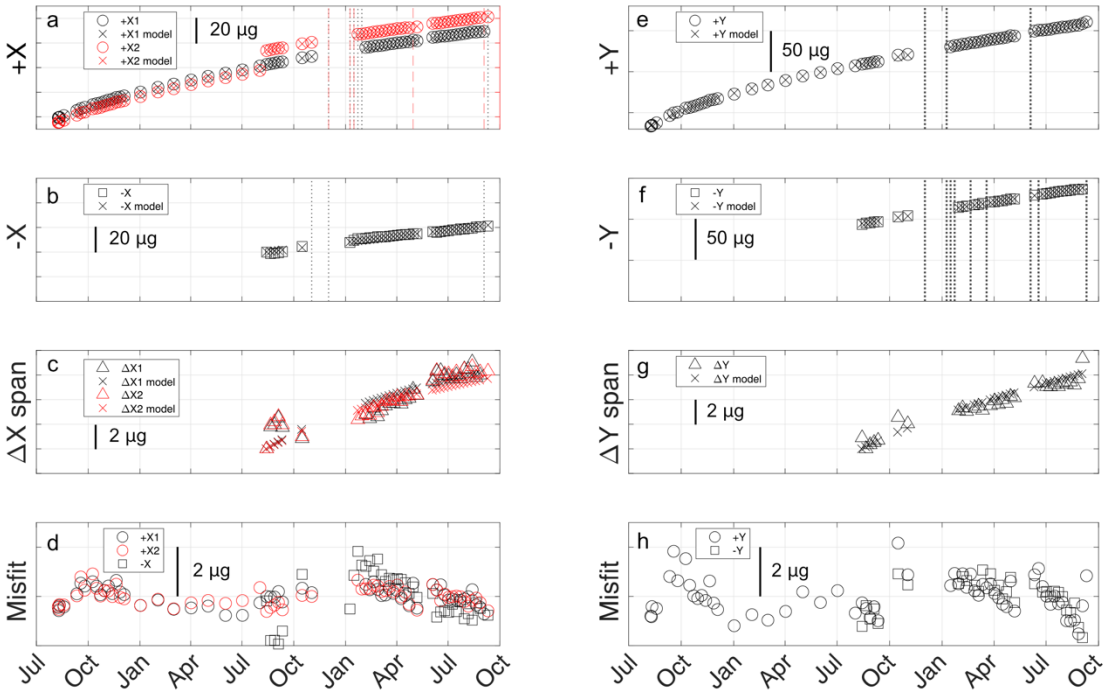

Figure S2. Calibration results for the Axial Seamount SCTA at Location 1. (a) Calibration values for +X1 (black) and +X2 (red). (b) Calibration values for -X. (c) X span results (defined as +X minus -X). (d) Misfit of the exponential linear model (equation 5) for the +X1, +X2 and -X calibrations. (e-h) As for (a-d) except for Y calibrations. Vertical dotted lines in (a-b) and (e-f) indicate where anomalous calibrations have been excluded (see text).

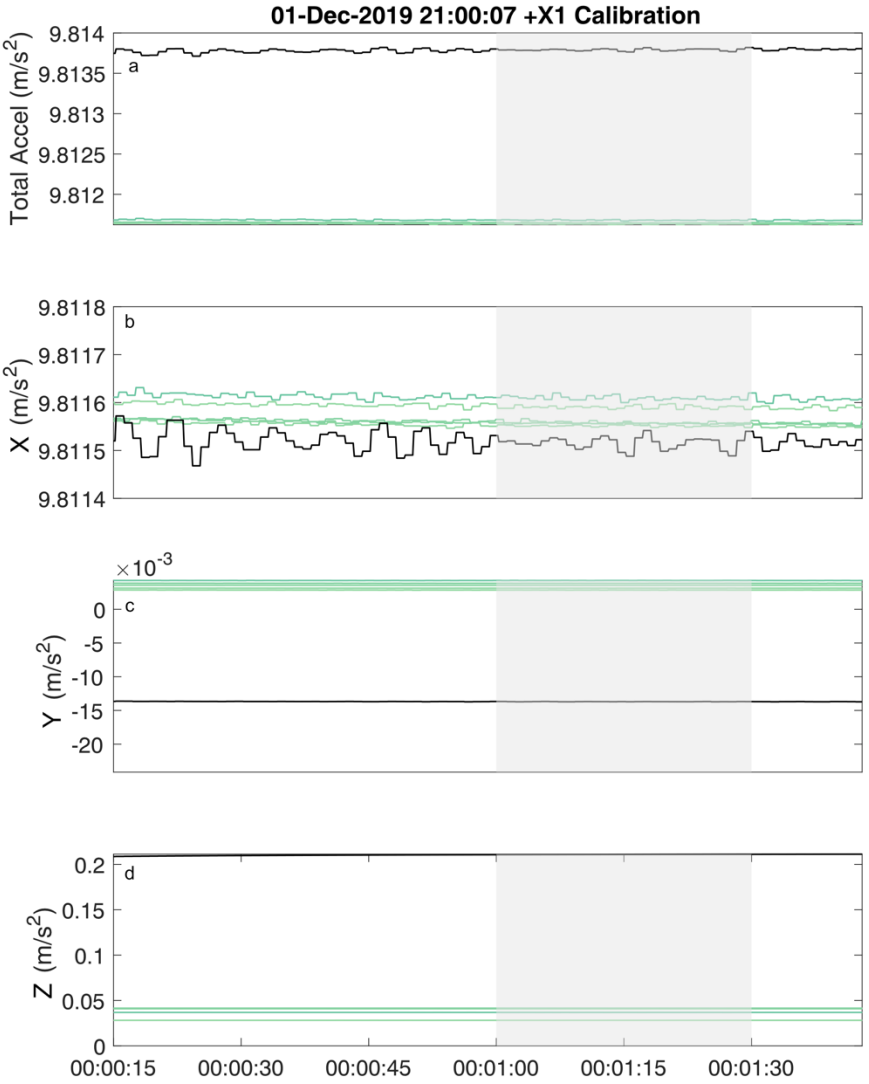

Figure S3. Acceleration observed during 6 +X1 calibrations on the SCTA at Axial Seamount Location 1 from August 20 – December 1, 2019 showing an anomalous calibration at the end of that period. (a) Total (b) X channel, (c) Y channel, and (d) Z channel acceleration. Time is referenced to the start the calibration interval and the curves are color coded by order of the calibration from pale green at the beginning to black at the end. Light gray shading shows the time interval used to obtain calibration values. The final calibration (black) is clearly inconsistent with the drift observed for other calibrations.

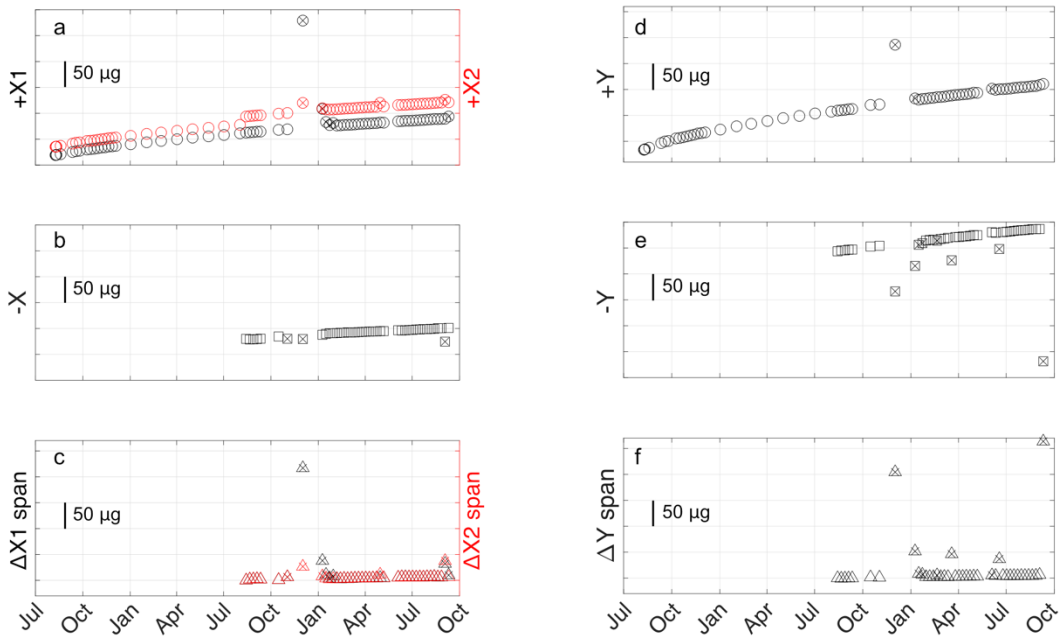

Figure S4. Calibration values for Axial Location 1 with anomalous calibrations included (symbols infilled with 'x'). (a-c) As for Figure S2a-c. (d-f) As for Figure S2e-h.

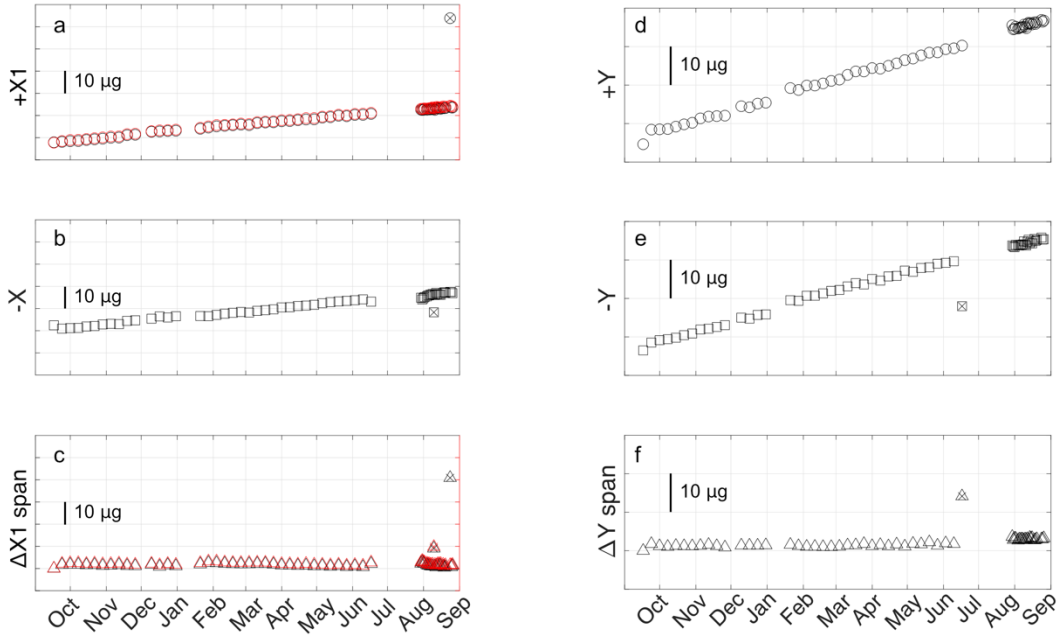

Figure S5. Calibration values for Axial Location 2 with anomalous calibrations plotted (symbols infilled with 'x'). (a-c) As for Figure 6a-c. (d-f) As for Figure 6e-h.

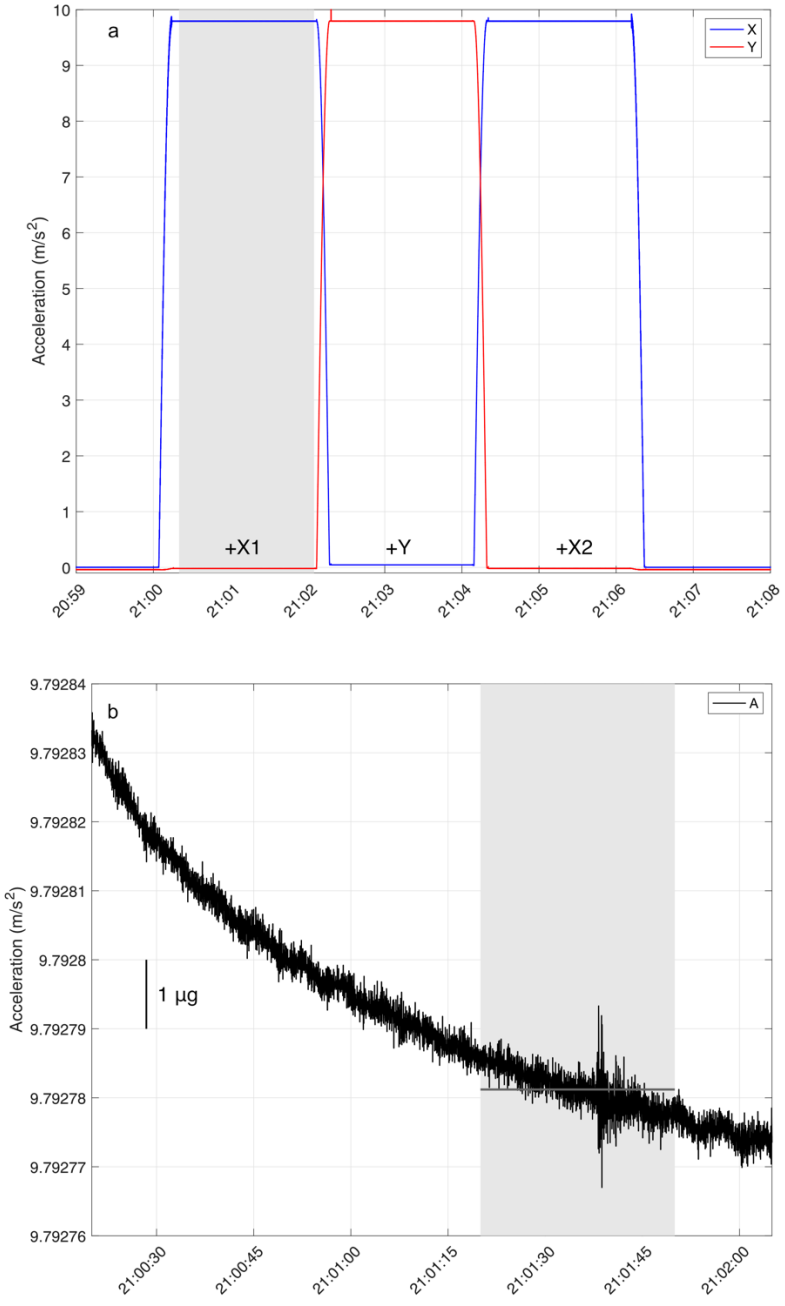

Figure S6. (a) X (blue) and Y channel (red) acceleration observations during a 3-orientation calibration sequence at PFO on 10/25/2018, with calibration orientations labeled. Gray shaded area indicates the time interval plotted in (b). (b) Total acceleration observed during the interval indicated in (a), after the sensor has stabilized in the +X1 orientation and prior to beginning the next rotation. Gray shaded area indicates the interval over which the acceleration is averaged to get a calibration value. The dark gray horizontal line indicates the calculated calibration value during the interval.

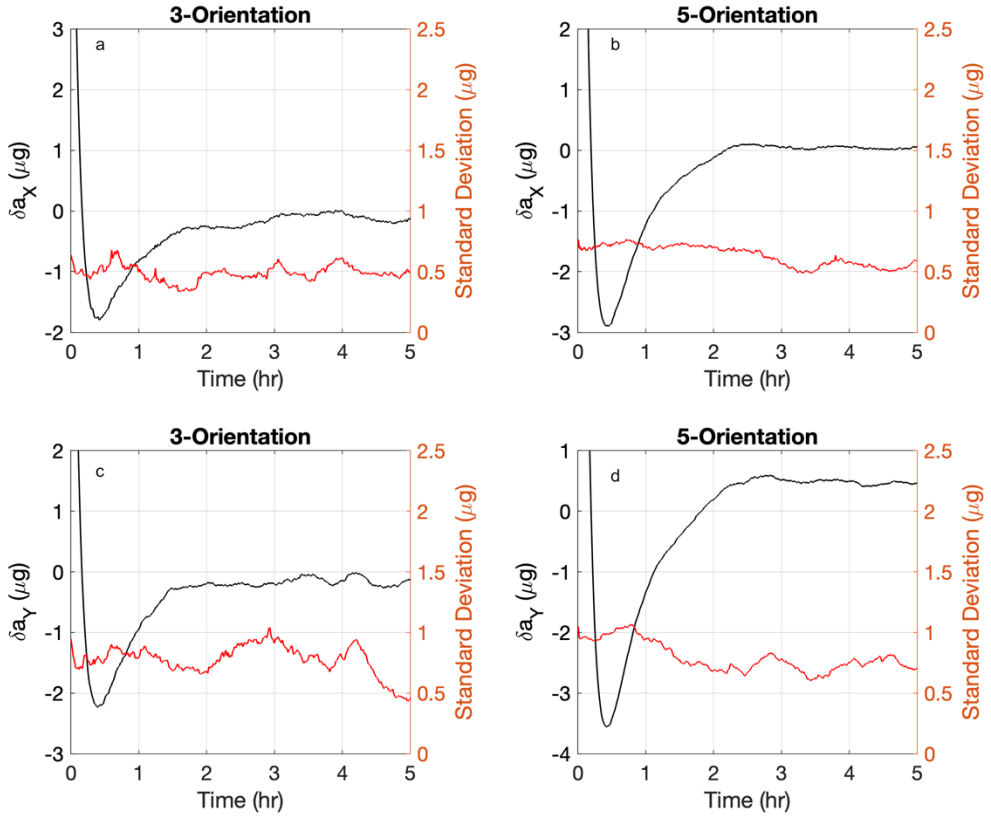

Figure S7. Transient accelerations (black lines) observed at Axial Seamount after the calibrations for (a) the X channel and the three-orientation sequence, (b) the X channel and the five-orientation sequence, (c) the Y channel and the three-orientation sequence and (d) the Y channel and the five-orientation sequence. The transients determined after first decimating the observed accelerations to a 1-minute time series and then by averaging the detrended accelerations observations after each calibration type. The standard deviation (red lines) will be a combination of any variation in the post-calibration transient and variations in environmental noise between intervals.

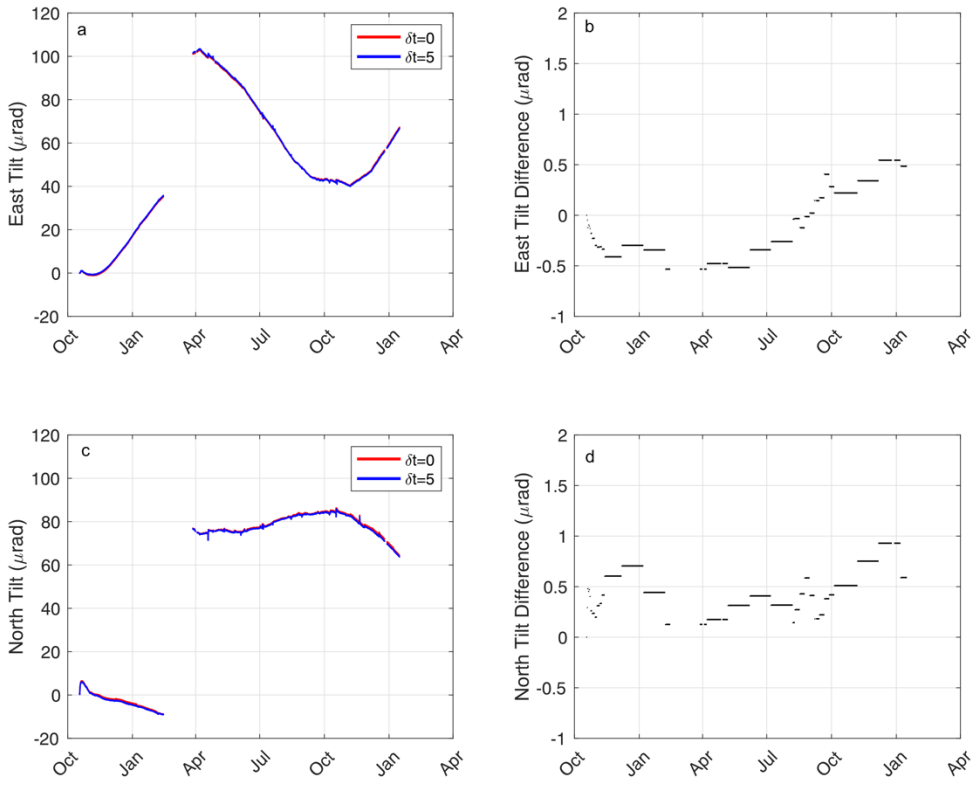

Figure S8. (a-b) Time series of one-minute averaged drift-corrected stitched tilt for Piñon Flat Observatory for 2018 to 2020 for (a) the east direction (-Y) and (b) the north direction (+X) obtained using *dt* = 0 (red) and *dt* = 5 hours (blue) in equation (9). (c-d) The resulting difference in the tilt time series (*dt* = 0 minus *dt* = 5 hours) showing an accumulated offset for the two interpolation methods.

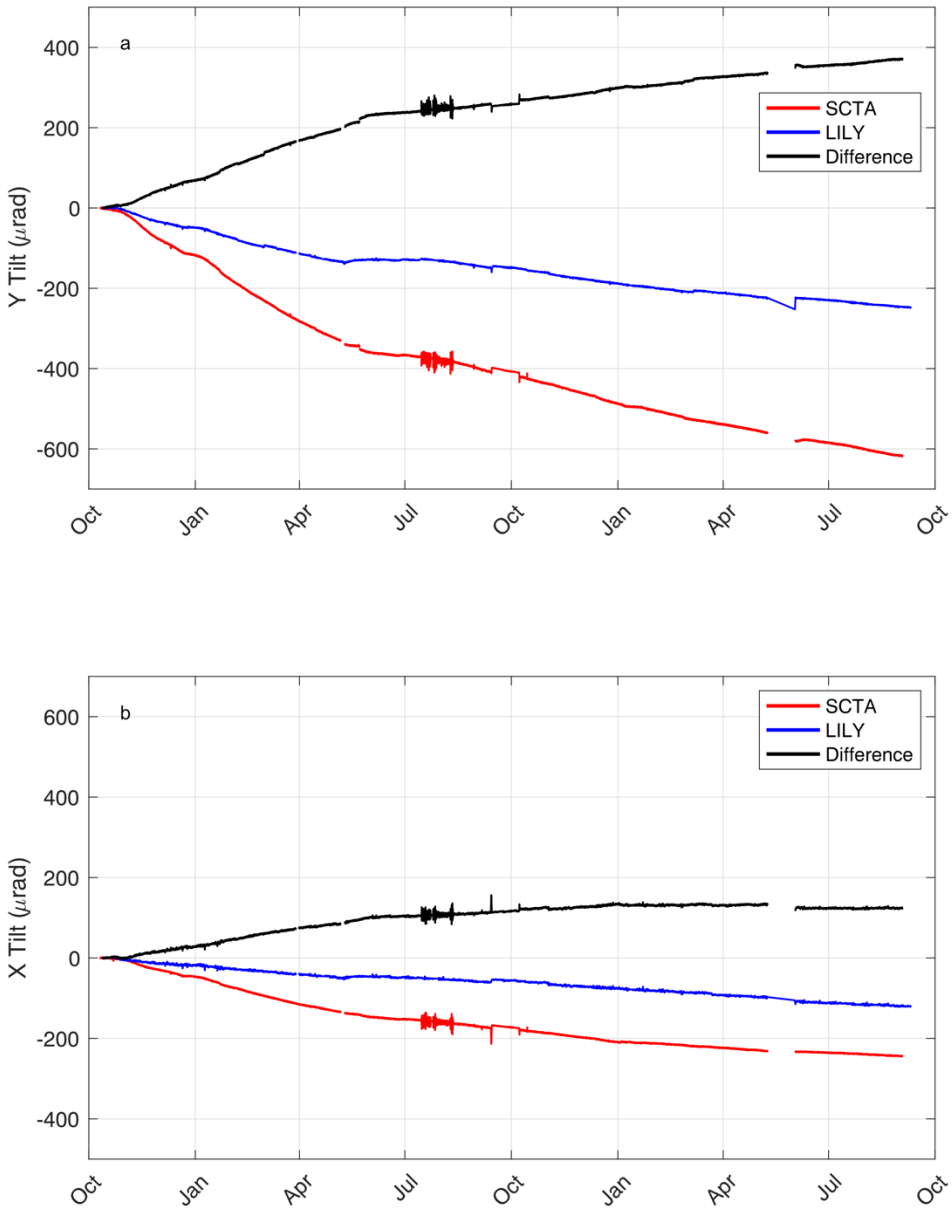

Figure S9. Time series of 1-minute averaged tilt for Axial Seamount Location 1 from 2018 to 2020 for the (a) Y channel (approximately west) and (b) X channel (approximately north). Each panel shows the drift corrected SCTA data (red), stitched using *dt* = 5 hours in equation (9), the LILY tilt meter data rotated into the SCTA channel coordinates (blue) and the difference (LILY – SCTA) (black). The sign convention is positive for a downward tilt.

Table S1. Details of calibrations at Axial Seamount Location 1 indicating the date, calibration values relative to the first calibration, and the rate of drift over the previous measurement interval obtained from differencing the calibration values. Gray shading indicates anomalous calibrations that are evident by unreasonable apparent rates of drift.

Date	+X1 (ug)	∂+X1 / ∂t (ug/yr)	+Y (ug)	∂+Y / ∂t (ug/yr)	-Y (ug)	∂-Y / ∂t (ug/yr)	+X2 (ug)	∂+X2 / ∂t (ug/yr)	-X (ug)	∂-X / ∂t (ug/yr)	Comment
2018-08-08	0.00		0.00				0.00				
2018-08-09	0.04	14	0.34	125			0.06	23			
2018-08-10	0.42	138	1.13	286			0.43	134			
2018-08-18	1.70	59	3.94	128			1.80	62			
2018-08-22											OOI power loss
2018-08-24											OOI power return
2018-09-10	5.92	67	12.90	142			5.97	66			
2018-09-17	7.43	79	16.09	166			7.84	98			
2018-09-24	8.37	49	16.99	47			8.39	29			
2018-10-08	10.62	58	21.87	127			11.15	72			
2018-10-15	11.44	43	22.69	43			11.58	23			
2018-10-22	12.08	33	24.10	74			12.27	36			
2018-10-29	13.23	60	25.78	88			13.46	62			
2018-11-05	14.37	59	27.65	97			14.42	50			
2018-11-12	15.00	33	29.13	77			15.13	37			
2018-11-19	16.47	76	31.57	127			16.56	74			
2018-11-26	16.91	23	32.27	37			16.93	19			
2018-12-03	17.70	41	33.57	68			17.77	44			
2019-01-01	20.84	40	38.99	68			21.05	41			
2019-02-01	24.64	45	45.37	75			24.84	45			
2019-03-01	27.33	35	50.10	62			27.44	34			
2019-04-01	30.60	38	55.60	65			30.81	40			
2019-05-01	33.62	37	61.09	67			33.77	36			
2019-06-01	36.15	30	65.30	50			36.46	32			
2019-07-01	38.84	33	70.11	58			39.18	33			

2019-08-01	42.02	37	73.53	40			42.28	37			
2019-08-13	43.28	38	75.59	63	0.00		58.40		0.00		
2019-08-20	43.84	30	76.32	38	-1.63	-85	59.12	37	1.22	64	
2019-08-27	44.41	30	76.90	30	-1.87	-13	59.77	34	0.83	-21	
2019-09-03	45.20	41	78.29	72	-3.07	-63	60.44	35	0.59	-12	
2019-09-10	45.34	7	78.66	19	-3.27	-10	60.68	13	-0.32	-48	
2019-10-15	48.67	35	86.47	81	-9.22	-62	63.95	34	-4.56	-44	
2019-11-01	49.80	24	87.41	20	-10.68	-31	65.18	26	-0.23	93	
2019-12-01	259.89	2556	202.64	1402	77.42	1072	84.64	237	0.43	8	
2020-01-08	89.15	-1640	99.18	-994	28.18	-473	74.26	-100	-7.84	-79	
2020-01-15	63.86	-1319	96.68	-131	-12.58	-2125	72.00	-117	-9.60	-91	
2020-01-22	57.92	-310	98.07	72	-15.69	-162	71.74	-14	-10.96	-71	
2020-01-29	61.98	212	98.54	25	-20.75	-264	71.87	7	-10.79	9	
2020-02-05	57.19	-250	99.84	68	-21.81	-56	72.36	26	-11.12	-18	
2020-02-12	57.47	15	100.18	18	-22.44	-33	72.86	26	-11.74	-32	
2020-02-19	58.28	42	101.61	75	-20.44	104	73.48	32	-11.70	2	
2020-02-26	58.47	10	101.82	11	-23.83	-177	73.92	23	-12.58	-46	
2020-03-04	58.71	12	102.53	37	-24.37	-28	74.18	14	-12.33	13	
2020-03-11	59.21	26	103.86	69	-26.02	-86	74.70	27	-12.44	-6	
2020-03-18	59.95	38	104.60	39	17.38	2263	75.34	33	-12.96	-27	
2020-03-25	60.25	16	105.65	54	-27.45	-2337	75.60	14	-13.28	-17	
2020-04-01	60.84	31	106.15	26	-27.56	-6	76.34	39	-13.71	-22	
2020-04-08	60.99	8	106.85	37	-28.56	-52	76.33	-1	-14.07	-19	
2020-04-15	61.59	31	107.48	33	-28.79	-12	77.00	35	-14.32	-13	
2020-04-22	61.66	4	108.26	41	-29.87	-56	76.97	-2	-14.27	3	
2020-04-29	63.05	72	110.19	100	-31.23	-71	84.66	401	-14.92	-34	
2020-05-06	62.51	-28	109.85	-18	-31.00	12	77.67	-365	-14.88	2	
2020-05-09											OOI power loss
2020-06-02											OOI power return
2020-06-03	65.33	37	117.88	105	-36.80	-76	80.56	38	-16.59	-22	
2020-06-10	65.59	13	115.72	-112	-35.70	57	80.79	12	-16.02	30	
2020-06-17	66.25	35	116.86	59	-4.39	1633	80.82	2	-16.61	-31	

2020-06-24	66.30	2	117.01	8	-36.93	-1697	81.54	38	-17.05	-23	
2020-07-01	66.56	13	117.50	25	-37.75	-42	81.87	17	-17.37	-17	
2020-07-08	67.05	26	118.04	29	-38.31	-30	82.35	25	-18.09	-37	
2020-07-15	67.47	22	119.25	63	-39.33	-53	82.83	25	-18.17	-4	
2020-07-22	67.92	23	119.82	30	-40.07	-39	83.26	22	-18.95	-40	
2020-07-29	68.44	27	120.76	49	-40.69	-32	83.52	14	-18.66	15	
2020-08-05	68.98	28	120.88	7	-40.93	-13	83.78	14	-19.25	-31	
2020-08-12	69.71	38	121.74	45	-41.62	-36	84.47	36	-19.37	-6	
2020-08-19	69.54	-9	122.67	48	-42.79	-61	85.01	28	-20.46	-57	
2020-08-26	69.91	19	122.98	16	-42.59	10	85.28	14	-20.62	-8	
2020-09-02	70.09	9	125.00	105	-42.96	-19	90.65	280	5.43	1358	
2020-09-09	74.46	228	127.09	109	212.20	13305	85.84	-251	-21.12	-1384	

Table S2. Details of calibrations at Axial Seamount Location 2 indicating the date, calibration values relative to the first calibration, and the rate of drift over the previous measurement interval obtained from differencing the calibration values. Gray shading indicates anomalous calibrations that are evident by unreasonable apparent rates of drift.

Date	+X1 (ug)	∂+X1 / ∂t (ug/yr)	+Y (ug)	∂Δ+Y / ∂t (ug/yr)	-Y (ug)	∂Δ-Y / ∂t (ug/yr)	+X2 (ug)	∂Δ+X2 / ∂t (ug/yr)	-X (ug)	∂Δ-X / ∂t (ug/yr)	Comment
2020-09-16	0.00		0.00		0.00		0.00		0.00		
2020-09-22											OOI power loss
2020-09-23											OOI power return
2020-09-23	0.19	10	3.80	198	-2.03	-106	0.73	38	1.50	78	
2020-09-30	0.52	17	3.75	-3	-2.88	-45	1.21	25	1.27	-12	
2020-10-07	0.57	2	3.96	11	-2.92	-2	1.30	5	1.18	-5	
2020-10-14	1.06	26	4.59	33	-3.51	-31	1.63	17	0.57	-32	
2020-10-21	1.34	15	5.18	31	-3.96	-24	2.02	20	0.32	-13	
2020-10-28	1.64	15	5.59	21	-4.39	-23	2.37	18	-0.39	-37	
2020-11-04	2.05	21	6.73	60	-5.43	-54	2.79	22	-0.68	-15	
2020-11-11	2.15	5	7.20	25	-5.64	-11	2.85	3	-0.52	8	
2020-11-18	3.19	54	7.31	6	-6.10	-24	3.86	53	-2.00	-77	
2020-11-25	3.38	10	7.43	6	-6.56	-24	4.05	10	-2.26	-13	
2020-12-02	3.90	27	8.55	58	-7.67	-58	4.63	30	-2.68	-22	
2020-12-09	4.74	44	9.89	70	-8.51	-44	5.21	30	-2.98	-16	
2020-12-16	4.88	7	9.60	-15	-8.23	14	5.56	18	-4.01	-54	
2020-12-23	5.09	11	10.57	50	-9.21	-51	5.70	7	-3.53	25	
2020-12-30	5.20	5	10.81	13	-9.36	-8	5.87	9	-4.10	-30	
2021-01-06	5.49	15	11.43	33	-9.79	-23	6.34	24	-4.31	-10	
2021-01-13											OOI power loss
2021-01-18											OOI power return
2021-01-20	6.09	16	14.61	83	-13.04	-85	6.70	10	-4.17	4	
2021-01-27	6.64	28	14.11	-26	-12.88	8	7.35	34	-4.10	3	
2021-02-03	7.17	27	15.27	60	-14.21	-69	7.94	31	-4.69	-31	

2021-02-10	7.43	14	15.27	0	-14.21	0	8.05	5	-5.24	-28	
2021-02-17	7.70	14	15.81	28	-14.82	-32	8.27	12	-5.64	-21	
2021-02-24	7.97	14	16.47	34	-15.48	-35	8.63	19	-6.03	-20	
2021-03-03	7.75	-12	16.80	17	-15.71	-12	8.44	-10	-5.75	15	
2021-03-10	8.67	48	18.03	64	-16.62	-47	9.28	44	-6.54	-41	
2021-03-17	8.94	14	18.94	47	-17.49	-45	9.52	12	-6.81	-14	
2021-03-24	9.02	4	18.92	-1	-17.14	19	9.63	6	-7.20	-20	
2021-03-31	9.47	24	19.80	46	-18.56	-75	10.16	27	-8.06	-45	
2021-04-07	9.56	5	19.64	-8	-18.13	23	10.24	4	-8.17	-6	
2021-04-14	9.98	21	20.64	52	-19.31	-61	10.60	19	-8.74	-30	
2021-04-21	10.27	16	21.02	20	-19.36	-3	11.07	25	-8.90	-8	
2021-04-28	10.33	3	21.87	44	-20.74	-72	11.09	1	-9.25	-18	
2021-05-05	11.13	41	22.27	21	-20.42	17	11.75	35	-9.95	-36	
2021-05-12	11.32	10	23.12	44	-21.42	-52	11.98	12	-10.44	-26	
2021-05-19	11.97	34	23.82	37	-21.59	-9	12.61	33	-10.76	-17	
2021-05-26	11.76	-11	23.89	4	-22.53	-49	12.40	-11	-11.01	-13	
2021-06-02	12.33	30	24.71	43	-22.76	-12	12.98	30	-11.30	-15	
2021-06-09	12.37	2	24.94	12	-23.16	-21	13.07	5	-11.70	-21	
2021-06-16	12.78	22	25.91	51	-11.59	603	13.50	23	-10.71	51	
2021-07-29	14.68	16	30.91	42	-27.28	-133	15.28	15	-12.43	-15	
2021-07-30	14.61	-28	29.85	-386	-27.00	100	15.15	-48	-11.65	287	
2021-07-31	14.63	7	30.02	61	-27.23	-82	15.25	36	-12.15	-185	
2021-08-01	14.91	104	30.56	196	-27.41	-67	15.47	81	-12.72	-207	
2021-08-02	15.00	32	30.56	2	-27.96	-198	15.64	59	-13.20	-176	
2021-08-03	14.69	-114	30.07	-182	-27.38	208	15.32	-115	-13.02	66	
2021-08-04	14.81	45	30.22	57	-27.26	47	15.46	51	-13.45	-155	
2021-08-05	14.81	2	30.38	57	-27.48	-82	15.48	6	-13.48	-11	
2021-08-06	14.89	28	30.41	11	-27.41	26	15.60	43	-13.82	-126	
2021-08-07	14.89	0	30.48	26	-27.55	-51	15.56	-14	-13.86	-14	
2021-08-08	15.15	93	31.10	226	-28.33	-286	15.95	143	-14.11	-90	
2021-08-09	14.92	-81	30.52	-211	-27.52	296	15.65	-111	-5.86	3010	
2021-08-10	14.65	-100	30.16	-133	-27.27	93	15.35	-110	-13.67	-2850	
2021-08-11	15.26	223	31.29	412	-28.23	-351	16.06	261	-14.66	-360	
2021-08-12	15.48	79	31.58	107	-28.75	-191	16.08	6	-14.13	191	
2021-08-13	15.18	-109	31.30	-103	-27.89	315	15.93	-54	-13.92	79	
2021-08-14	15.25	25	31.52	82	-28.28	-142	15.90	-12	-13.85	23	

2021-08-15	15.09	-58	31.15	-136	-27.82	167	15.87	-9	-13.78	25	
2021-08-16	15.38	106	31.44	105	-28.17	-127	16.11	87	-14.24	-167	
2021-08-17	15.52	50	31.69	93	-28.96	-288	16.35	88	-14.62	-138	
2021-08-18	15.34	-65	31.28	-149	-28.44	189	16.07	-104	-14.89	-98	
2021-08-19	15.41	28	31.71	157	-28.68	-86	16.22	55	-14.68	74	
2021-08-20	15.41	-3	31.36	-127	-28.63	16	16.16	-21	-14.72	-13	
2021-08-21	15.39	-6	31.54	63	-28.86	-81	16.09	-26	-14.13	213	
2021-08-22	15.64	91	31.84	110	20.00	17833	16.18	32	-16.65	-919	
2021-08-23	55.94	14710	32.31	170	-29.32	-18001	16.64	168	-15.06	580	
2021-08-24	15.72	-14682	31.84	-170	-28.80	187	16.50	-51	-15.05	5	
2021-08-25	15.63	-32	32.17	119	-28.88	-29	16.23	-97	-14.47	209	
2021-08-26	15.82	66	32.41	90	-29.12	-89	16.42	68	-14.63	-56	

Table S3. Details of calibrations at Piñon Flat Observatory indicating the date, calibration values relative to the first calibration, and the rate of drift over the previous measurement interval obtained from differencing the calibration values.

Date	+X1 (ug)	Δ+X1 (ug/yr)	+Y (ug)	Δ+Y (ug/yr)	-Y (ug)	Δ-Y (ug/yr)	+X2 (ug)	Δ+X2 (ug/yr)	-X (ug)	Δ-X (ug/yr)	Comment
2018-10-18	0.00		0.00				0.00				
2018-10-19	-4.15	-1514	-3.69	-1348			-4.10	-1498			
2018-10-20	-6.91	-1010	-5.90	-805			-6.92	-1028			
2018-10-21	-9.11	-802	-8.00	-766			-9.07	-785			
2018-10-22	-10.69	-576	-9.27	-465			-10.75	-613			
2018-10-23	-12.06	-501	-10.48	-441			-12.07	-483			
2018-10-25	-13.96	-346	-12.36	-342			-13.97	-346			
2018-10-29	-15.84	-172	-14.42	-188			-15.75	-163			
2018-11-01	-16.64	-97	-15.60	-144			-16.61	-104			
2018-11-05	-17.19	-49	-16.42	-75			-17.15	-49			
2018-11-08	-17.11	9	-16.86	-53			-17.14	2			
2018-11-12	-16.98	13	-17.39	-48			-16.95	17			
2018-12-06	-17.72	-11	-20.93	-54			-17.55	-9			
2019-01-06	-19.00	-15	-25.21	-50			-18.83	-15			
2019-02-06	-18.76	3	-26.64	-17			-18.85	0			
2019-02-14											Local computer failure
2019-03-28											Computer replaced
2019-03-31											PFO power outage (?)
2019-04-03											PFO power restored (?)
2019-04-06	-11.93	42	-23.00	22			-12.68	38			
2019-04-27											PFO power outage (?)

2019-04-29											PFO power restored (?)
2019-05-06	4.02	194	-6.40	202			3.32	195			
2019-06-06	17.00	153	9.86	191			16.65	157			
2019-07-06	32.88	193	29.09	234			32.68	195			
2019-08-06	47.31	170	49.54	241			47.66	176			
2019-08-09	48.80	182	51.54	243	0.00		70.16	2738	0.00	0	
2019-08-16	51.22	126	55.29	195	-3.34	-174	72.69	132	-1.82	-95	
2019-08-23	52.70	77	57.77	130	-4.62	-67	74.34	86	-2.38	-29	
2019-08-30	55.58	150	61.24	181	-7.51	-151	77.63	171	-5.02	-138	
2019-09-06	58.52	154	63.60	123	-8.92	-74	80.60	155	-6.90	-98	
2019-09-08											PFO power outage (1 day)
2019-09-13	59.96	75	66.40	146	-11.24	-121	82.25	86	-7.97	-55	
2019-09-20	62.19	116	67.57	61	-11.93	-36	84.29	106	-9.32	-71	
2019-09-27	63.05	45	69.22	86	-13.88	-102	85.17	46	-9.60	-15	
2019-10-04	63.46	21	69.95	38	-14.43	-29	85.62	24	-9.66	-3	
2019-11-06	65.41	22	77.94	88	-20.95	-72	88.12	28	-11.22	-17	
2019-12-06	61.99	-42	74.85	-38	-19.37	19	84.28	-47	-10.43	10	
2019-12-25											PFO power outage (?)
2019-12-29											PFO power restored (?)
2020-01-06	54.67	-86	67.62	-85	-15.69	43	77.12	-84	-8.35	25	