IceCube DOM-Embedded MEMS Inclinometer/Accelerometer (iDOM)

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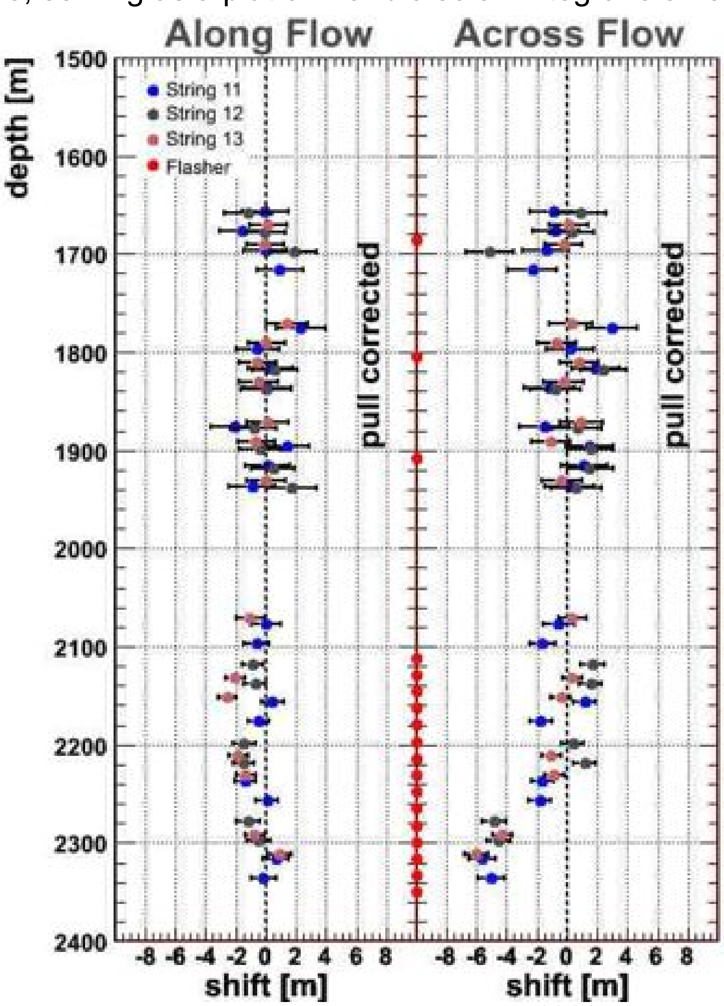
Motivation

The impact that shearing within the South Pole ice sheet may have on detector geometry and longevity has been an outstanding issue for IceCube. The collaboration has explored the use of muons and embedded light sources for tracking detector deformation, but these techniques typically have the disadvantages of poor resolution and potential biases.

At the same time, there is large uncertainty and much concern in both the scientific community and general public about the stability of ice sheets in the middle to long term. Poorly understood are the manner and degree to which the strain rate of large glaciers depends upon temperature and the presence of impurities. IceCube will encompass a cubic-kilometer of natural glacial ice, serving as a platform and also an integral element of the telescope, with large variations in both impurity content and temperature.

Figure 1 shows the results of tracking AMANDA strings 11, 12 and 13 over a 9 year baseline using flasher data. The bottom portions of these strings appear to have moved 5 meters during this time in a *cross-flow direction*, which is a surprising result. The ice in the depth range 2000-2450 m will hold over 40% of our sensors, and a gradual deformation of the initially calibrated array geometry could negatively impact event reconstruction capabilities.

Figure 2 shows a temperature profile of South Pole ice based on in situ thermistor readings from both AMANDA and IceCube. The extrapolation to bedrock is so poorly constrained that we do not know whether the ice sheet is melting at the bed or frozen.



meters since being deployed in 1998.

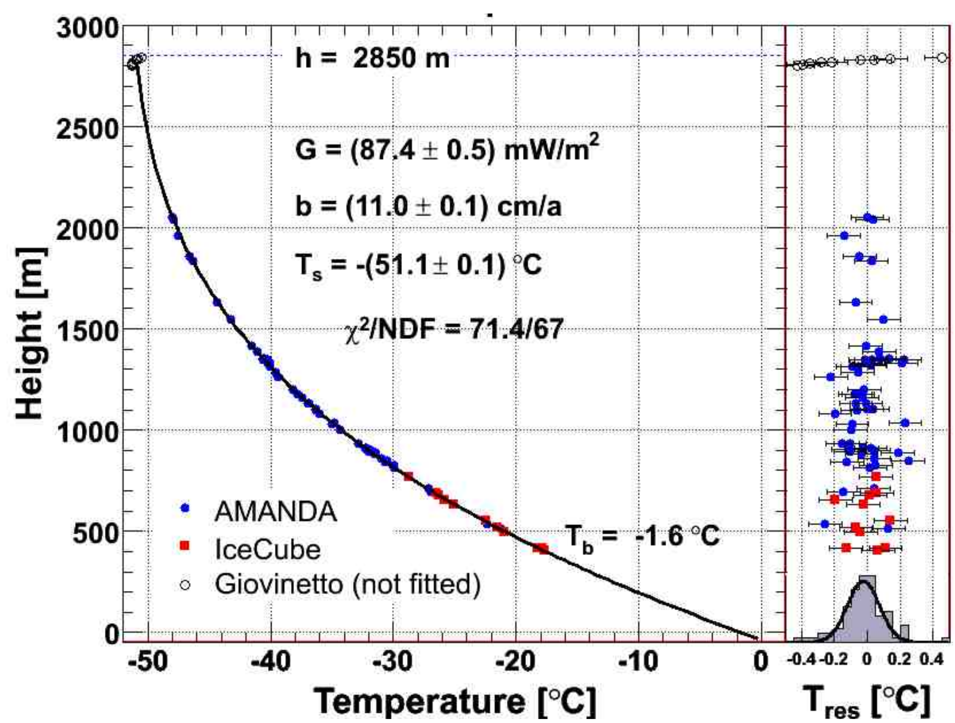


Fig. 2. Temperature fit and extrapolation to bedrock with AMANDA/IceCube thermistors.

Fig. 3. Possible influence of dust on the shear strength of glacial ice.

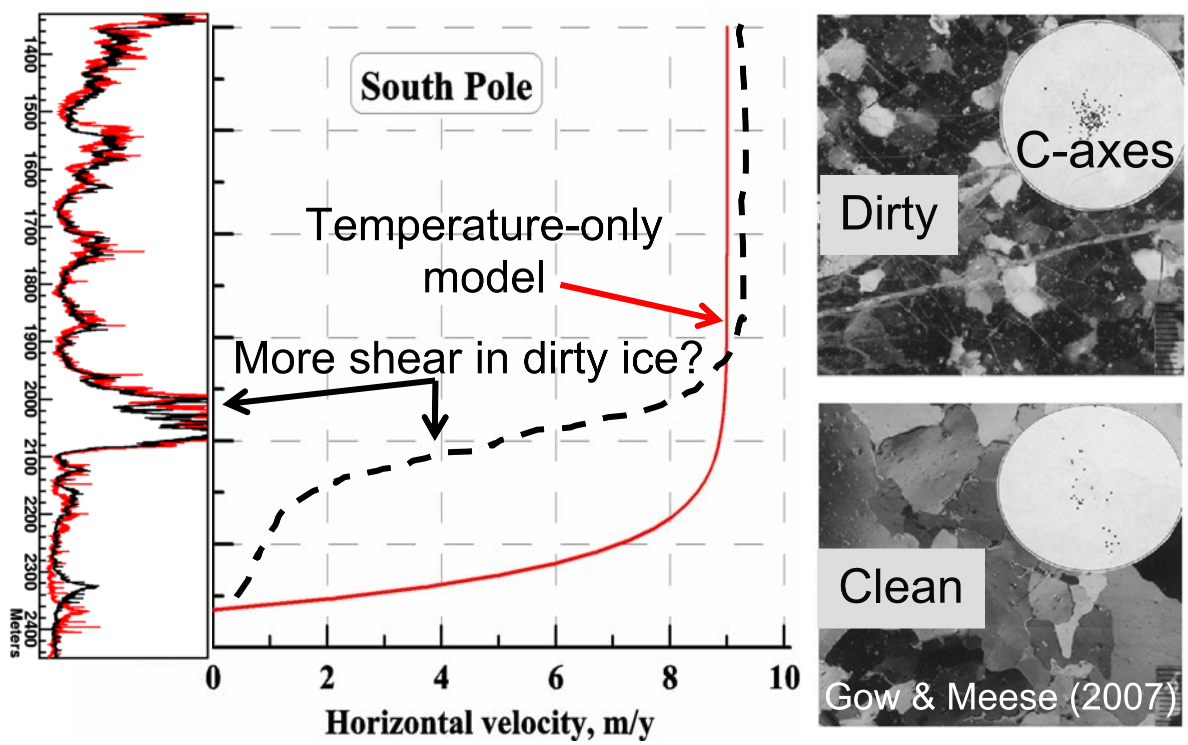
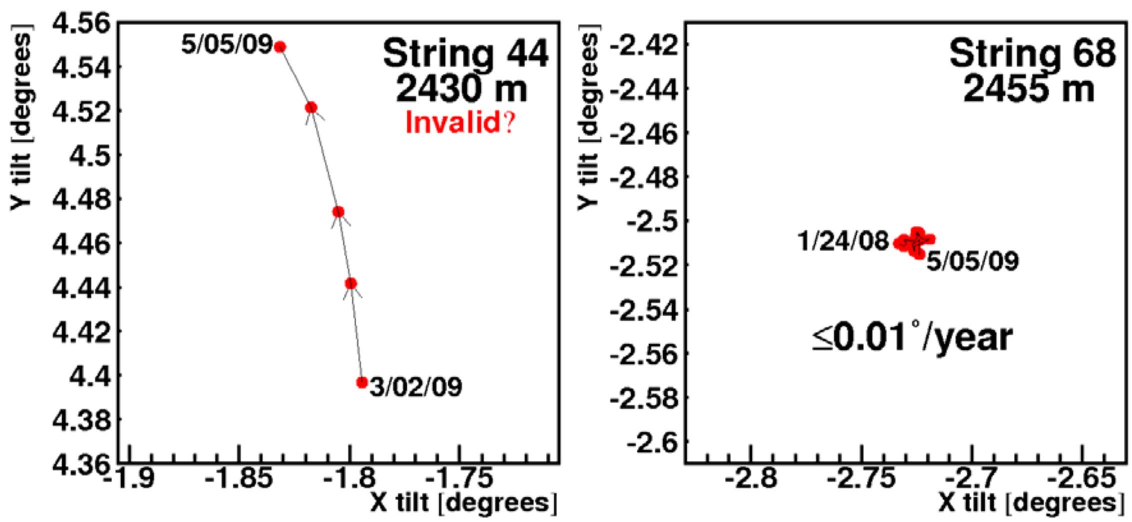


Figure 3 shows two possible shear curve models in which the ice is stuck to the bedrock. The simple model uses the temperature information from Figure 2 and makes assumptions about the way in which the strain rate increases with temperature. The second curve incorporates qualitative knowledge gained from other sites where it was found that shear concentrated in the dust bands, probably because of finer grains and faster fabric development.

Fig. 4 shows tilting of IceCube strings, measured by consecutive readings from three precision electrolytic inclinometers over more than one year. The change in shear with depth implied by the readings is difficult to reconcile with simple models of the strain rate of ice. In the figure, coordinates are local to each device and no absolute orientation is possible. By combining an inclinometer with a DOM, the direction of tilting can be reconstructed using flasher information. What little information we have obtained suggests that *different parts of the ice behave differently*. This means we are better off having measurements at lots of different points in space, rather than precise measurements at only a few points.



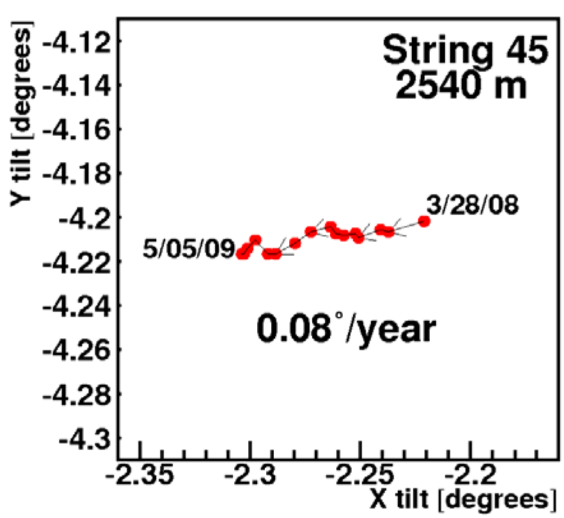


Fig. 4. Results from inclinometers deployed January 2008. Coordinates are local to each device and no absolute orientation is possible. The inclinometer on String 44 was installed just above DOM 59; the String 68 inclinometer was installed at the bottom of the string in the weight stack; the deepest inclinometer on String 45 was installed on an extension cable with a single weight on the end. The readings from the String 44 inclinometer, indicating substantial movement, were initially unstable and the result may not be valid.

Miniature Inclination/Acceleration Sensor

The ADIS16209 Analog Devices is a low-power dual-axis digital inclinometer and accelerometer. The ADIS16209 provides 0.025° angular resolution and 2.44×10^{-4} g acceleration resolution in a microelectromechanical integrated circuit.

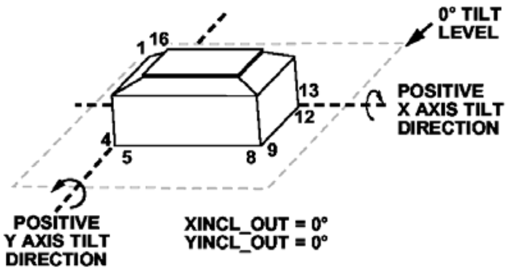
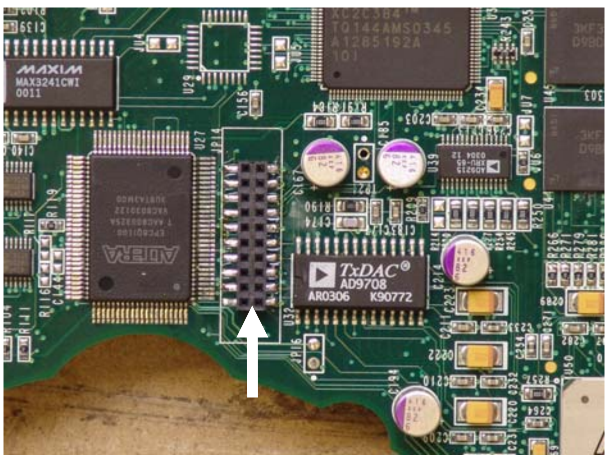


Fig. 5. Analog Devices ADIS16209.
Dimensions: 9.2 × 9.2 × 3.9 mm.
Power: <40 mW at 3.0 - 3.6 V.
Angular resolution: <0.025°.

The MEMS chip has been integrated with a small custom PCB board to be mounted as a mezzanine card on top of the DOM main board. The inclinometer circuit will attach to the unused FPGA connector JP14 (Fig. 6). The FPGA will emulate an SPI interface in the DOM firmware for communication with the sensor. Housekeeping code will periodically read out the inclinometers during normal data runs.



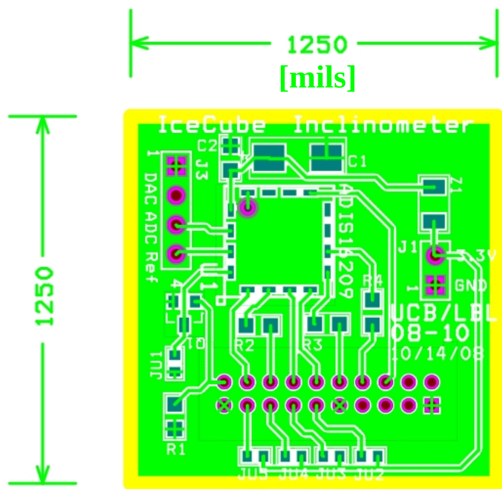


Fig. 6. (*Left*) Location for the inclinometer mezzanine board (*right*).

Impact

The inclinometer modules will be introduced into DOM production and logistic pipelines randomly to minimize impact. A record will be made of which DOMs have inclinometers installed, perhaps as part of the naming convention.

The design of the iDOM is such that:

- The inclinometer results in low (<1%) additional DOM power consumption.
- The circuitry and interface allow the inclinometer to be shut off.
- The inclinometer does not share any resource that could make the DOM inoperable or adversely affect physics data should the inclinometer fail (an unlikely occurrence).
- Readout of the inclinometer will have minimal impact on IceCube data acquisition operations or maintenance, since inclination data can be extracted with only a few seconds per year of CPU time. Data taking from the monitor stream is a fast and easily programmed operation for which examples already exist.

iDOM Testing

The inclinometer boards have been tested for functionality at a fixed angle. One of the 50 boards was used for burn-in and integration testing in the next section.

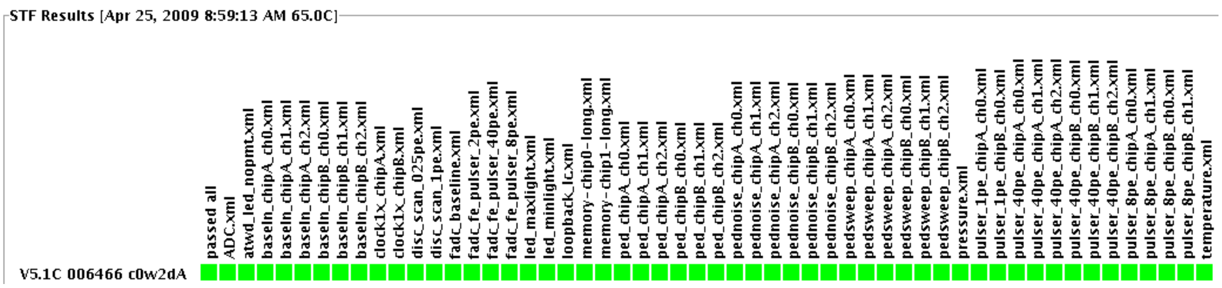
No.	Serial	Vcc (mV)	Temp	Tilt_X	Tilt_Y
1	8005	3229.10958	25.00	-13.550	-21.500
2	5009	3244.97894	25.00	-13.000	-16.575
3	8009	3246.19966	25.00	-13.350	-15.050
4	5007	3239.79088	25.47	-13.425	-18.175
5	2009	3243.45304	25.00	-13.025	-17.700
6	4004	3241.62196	25.00	-13.150	-16.575
7	1004	3245.58930	25.00	-13.825	-20.975
8	6007	3243.14786	25.00	-12.875	-16.850
9	1008	3231.85620	25.00	-12.550	-15.025
10	6005	3245.89448	24.53	-13.775	-18.750
11	7005	3243.14786	25.00	-13.900	-17.675
12	2003	3241.62196	24.53	-12.800	-17.350
13	7007	3244.06340	24.06	-13.200	-16.350
14	2005	3244.06340	24.53	-12.850	-16.125
15	4008	3237.95980	25.00	-13.350	-17.375
16	3005	3244.97894	25.00	-13.050	-17.375
17	4009	3247.72556	24.06	-13.150	-16.325
18	1007	3241.31678	25.00	-13.275	-18.400
19	7006	3236.73908	24.53	-13.750	-15.875
20	3008	3244.06340	25.00	-12.725	-17.425
21	2006	3232.77174	25.00	-12.950	-17.475
22	4007	3235.82354	25.00	-13.450	-17.375
23	3007	3235.51836	25.00	-13.250	-16.550
24	3002	3248.64110	25.00	-13.450	-14.175
25	5004	3246.19966	25.00	-13.300	-15.875
26	6009	3232.16138	24.53	-13.025	-17.200
27	6004	3236.43390	24.53	-13.025	-16.550
28	1009	3241.31678	24.06	-14.000	-15.275
29	3004	3227.58368	24.06	-13.300	-16.550
30	5008	3239.79088	25.00	-13.175	-14.700
31	3009	3244.97894	25.00	-13.700	-15.200
32	1005	3228.19404	25.00	-13.400	-16.500
33	2008	3235.21318	25.00	-13.325	-17.175
34	1002	3233.99246	24.53	-13.000	-17.675
35	6008	3245.28412	25.00	-13.000	-16.000
36	8006	3243.14786	25.00	-12.625	-15.800
37	6006	3244.06340	25.00	-13.275	-16.375
38	7004	3251.38772	25.00	-13.425	-16.625
39	5003	3229.41476	25.00	-13.400	-15.850
40	2007	3248.33592	25.00	-13.300	-16.225
41	7008	3242.84268	25.00	-13.250	-16.850
42	4005	3240.09606	25.00	-14.025	-17.500
43	5006	3243.75822	25.00	-12.800	-16.975
44	4006	3244.06340	24.06	-13.100	-17.250
45	8008	3243.45304	24.53	-13.375	-18.550
46	2002	3242.23232	25.00	-13.050	-17.725
47	5005	3233.68728	24.53	-12.975	-16.825
48	1003	3239.79088	24.06	-13.250	-17.325
49	2004	3248.64110	25.47	-13.300	-18.025

Burn-in Testing

A number of DOM mainboard burn-in tests were carried out over the full standard temperature profile. Tests included burn-in runs with 1) inclinometer off, 2) inclinometer on, and 3) continual readout of the inclinometer.

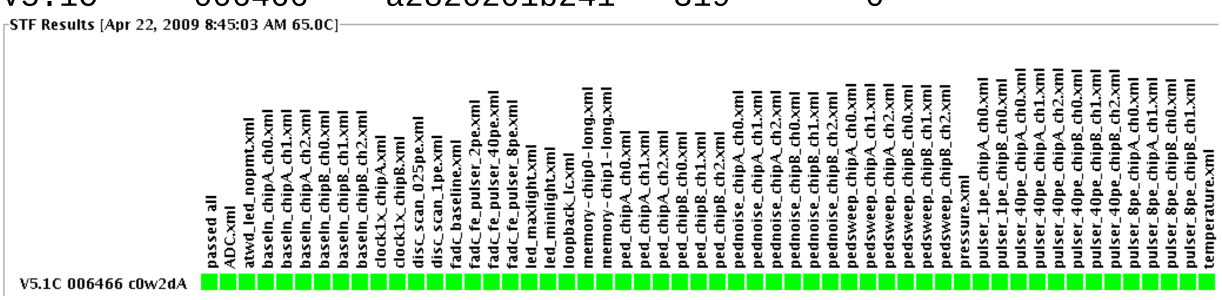
1) Burn-in, inclinometer off:

```
Sun Apr 26 13:57:18 PDT 2009
Period length: 49h 17m 34s  Boards tested:      1

Temperatures:  +65C +65C +65C +65C -10C -10C -15C -15C -20C -20C -
25C -25C -30C -30C -35C -35C -40C -40C -45C -45C -50C -50C -50C -
50C

BOARD     TAG       BOARD SERIAL   TEST      FAIL
V5.1C     006466    a2820201b241   319       0
```



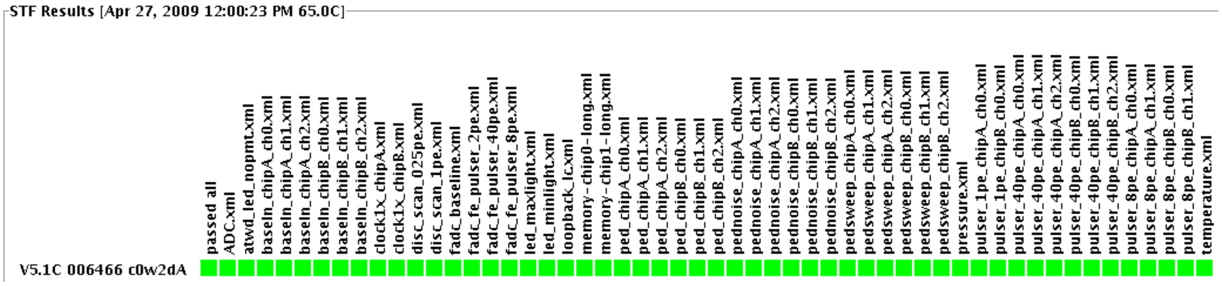
2) Burn-in, inclinometer on

```
Thu Apr 23 13:43:51 PDT 2009
Period length: 49h 59m 24s  Boards tested:      1

Temperatures:  +65C +65C +65C +65C -10C -10C -15C -15C -20C -20C -
25C -25C -30C -30C -35C -35C -40C -40C -45C -45C -50C -50C -50C -
50C

BOARD     TAG       BOARD SERIAL   TEST      FAIL
V5.1C     006466    a2820201b241   319       0
```



3) Burn-in, continual readout of inclinometer

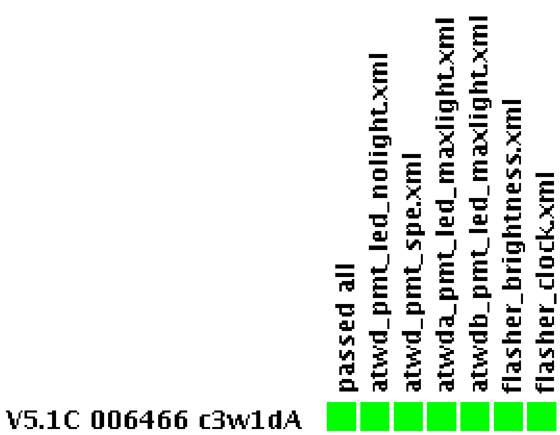
```
Tue Apr 28 16:58:22 PDT 2009
Period length: 49h 09m 16s  Boards tested:      1

Temperatures:  +65C +65C +65C +65C -10C -10C -15C -15C -20C -20C -
25C -25C -30C -30C -35C -35C -40C -40C -45C -45C -50C -50C -50C -
50C

BOARD     TAG       BOARD SERIAL   TEST      FAIL
V5.1C     006466    a2820201b241   319       0
```



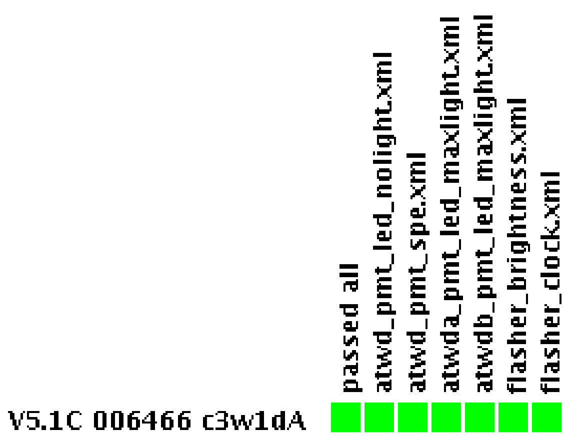
Integration testing

A completed DOM, including flasher board and PMT sealed in a pressure sphere, was run through an STF test with an inclinometer installed. The test was repeated with the inclinometer both on and off.

Inclinometer off



Inclinometer on



Inclinometer performance testing

Using draft FPGA code and scripts to exercise a prototype installed on a DOM main board, we found performance consistent with or better than specification (Fig. 7).

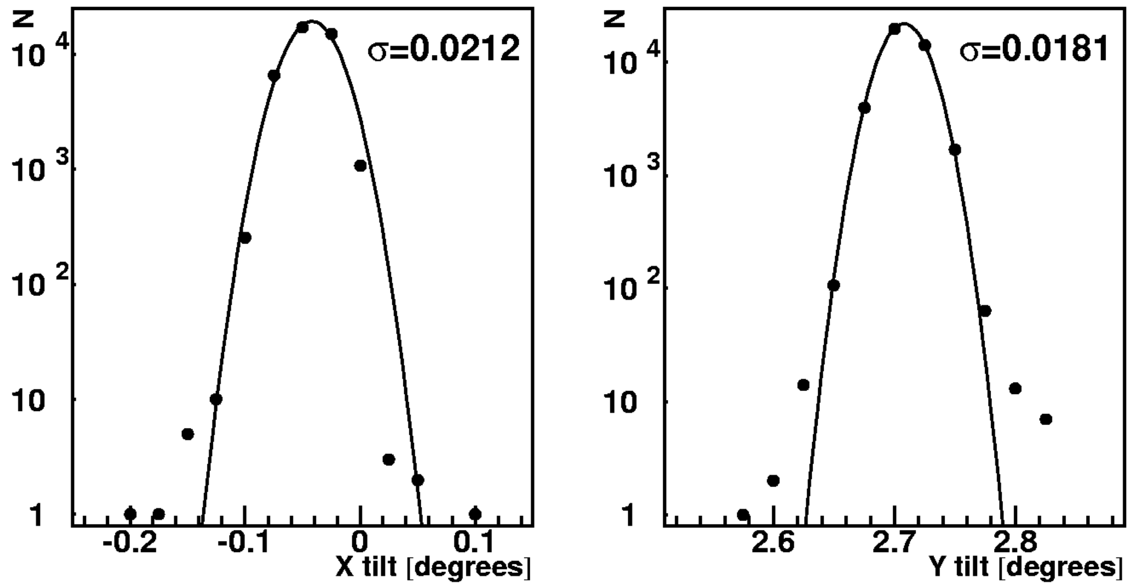


Fig. 7. Results from an ADIS16209 running through a DOM main board over four days. The inclinometer angular resolution exceeds product specification of 0.025°.

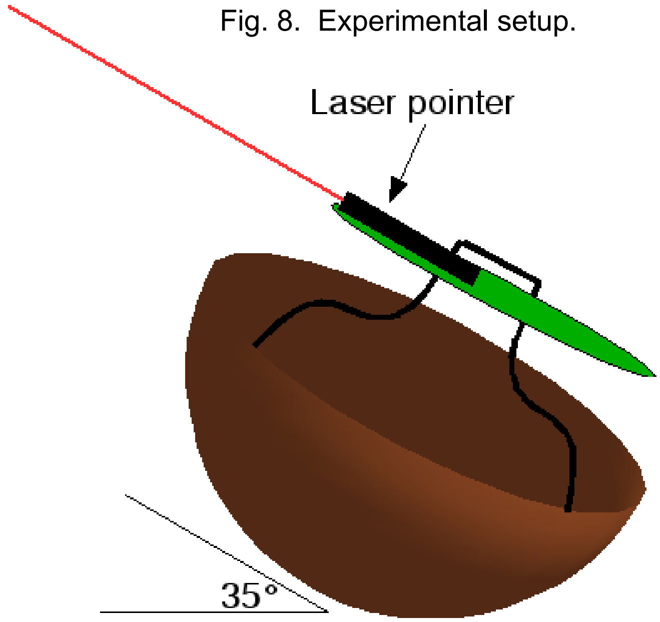
Gel creep test

A concern was raised that the performance of the iDOM in tracking ice movement could be compromised, if the gel which couples the PMT and hardware to the pressure sphere is capable of permanent deformation, or creep. Manufactured by Quantum Silicones, the gel is classified as a cross-linked elastomer that is resistant to flow.

When a stress is applied to a viscoelastic material such as a polymer, parts of the long polymer chain may change position, and this movement or rearrangement is called creep. Polymers remain a solid even when parts of the chains are rearranged in order to accompany the stress, and as this occurs, it creates a back stress in the material. When the original stress is taken away, the accumulated back stress will cause the polymer to return to its original form. *Upon application of a constant stress, the material deforms at a logarithmically decreasing rate, asymptotically approaching the steady state strain*.

Figure 8 shows the experimental setup in which potted DOM was fixed in an exaggerated stress position, tilted by 35° from the horizontal. A projected laser pointer registered tiny increments in the tilt of the PMT and hardware within the hemisphere over a period of several days. Two separate experiments were conducted and details are given below. In summary the gel behaves as expected, i.e., it is capable of elastic strain but does appear to flow substantially. These experiments were carried out at room temperature, and we can safely predict that the gel will be even more resistant to flow when in the ice and 40 to 60 degrees colder.

Fig. 8. Experimental setup.



Trial 1: The position of the PMT within the hemisphere was tracked for several days with a precision of ~0.001 degrees, an order of magnitude higher resolution than the MEMS inclinometer chip (0.025°). No movement was detectable.

Trial 2: A small weight was suspended from the flasher board to further exaggerate stress on the gel and to simulate a grossly offset center of gravity. The results are shown in Figure 10. After a 2-3 day adjustment to the stress, the gel reached a steady-state strain and did not distort further. The total displacement is below the resolution of the iDOM sensor.

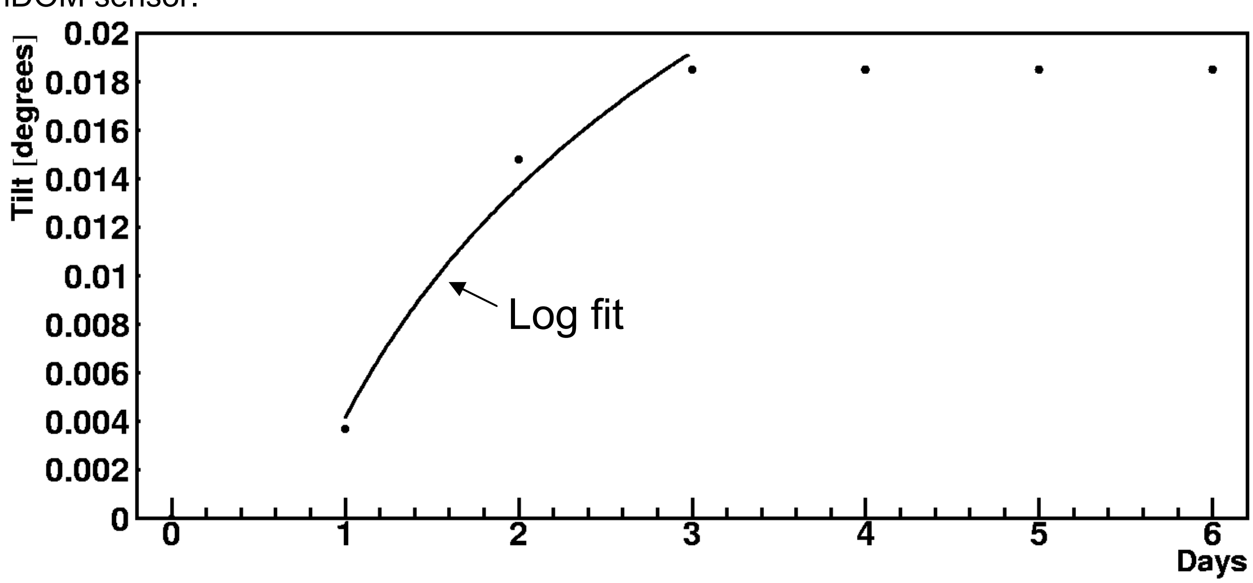
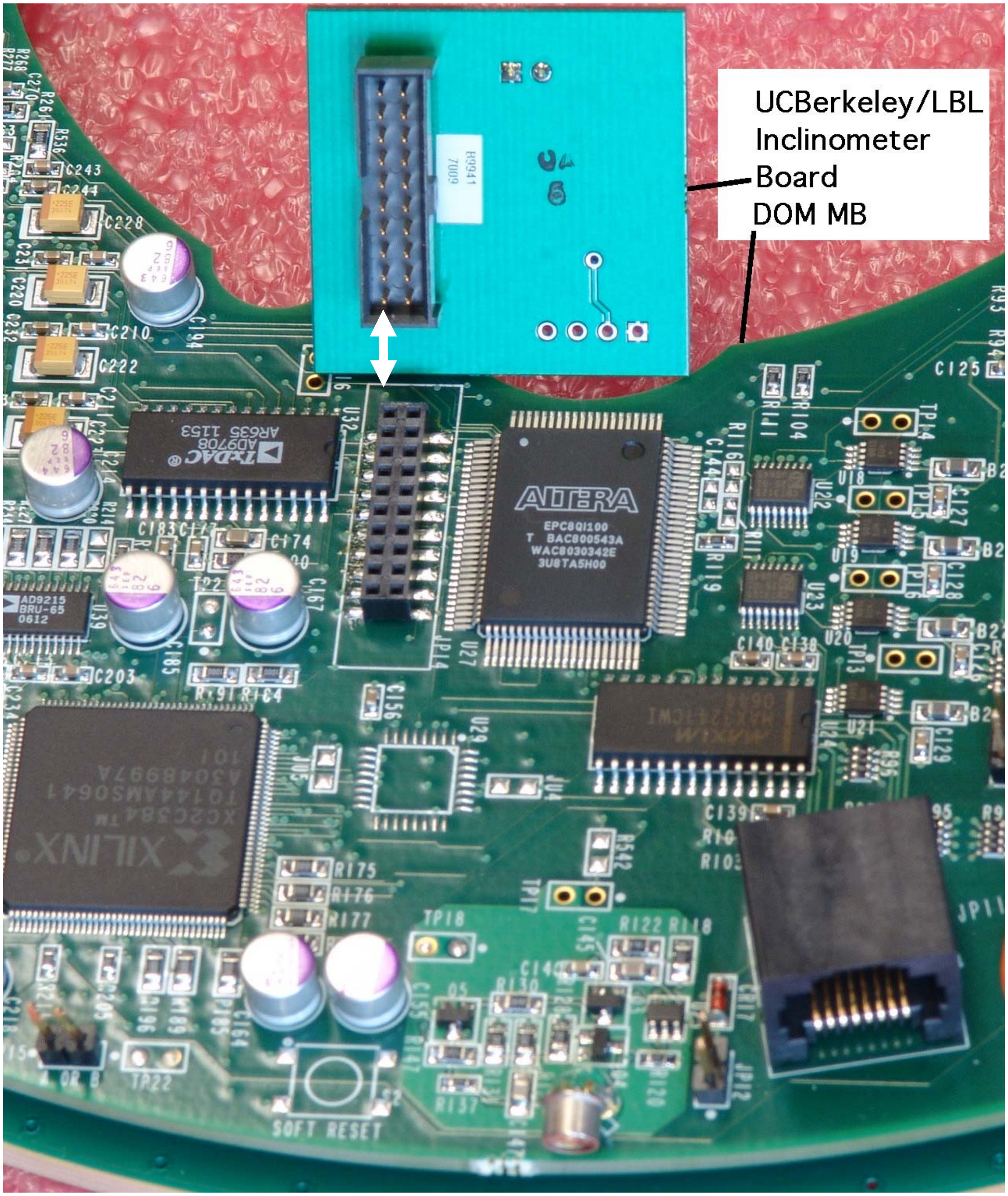


Fig. 9. Trial 2 results with added weight, showing deformation and stabilization phases.

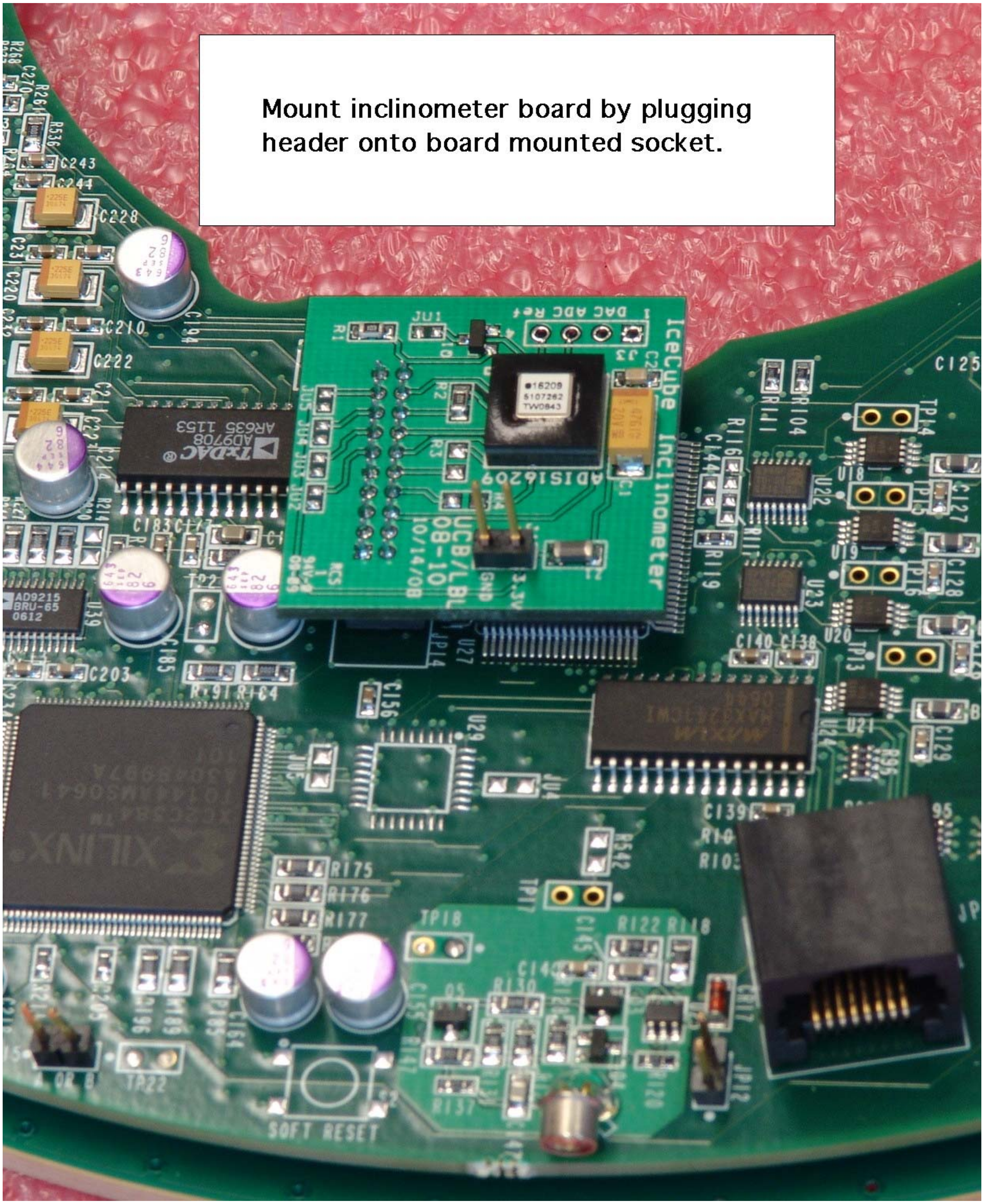
DOM inclinometer (iDOM) Installation

Mating connectors (Samtec SMM-110-02-S-D) have been added to 60 DOM main boards at location JP14. Fifty PCB inclinometer mezzanine cards have been built by Advanced Assembly in Aurora, CO.

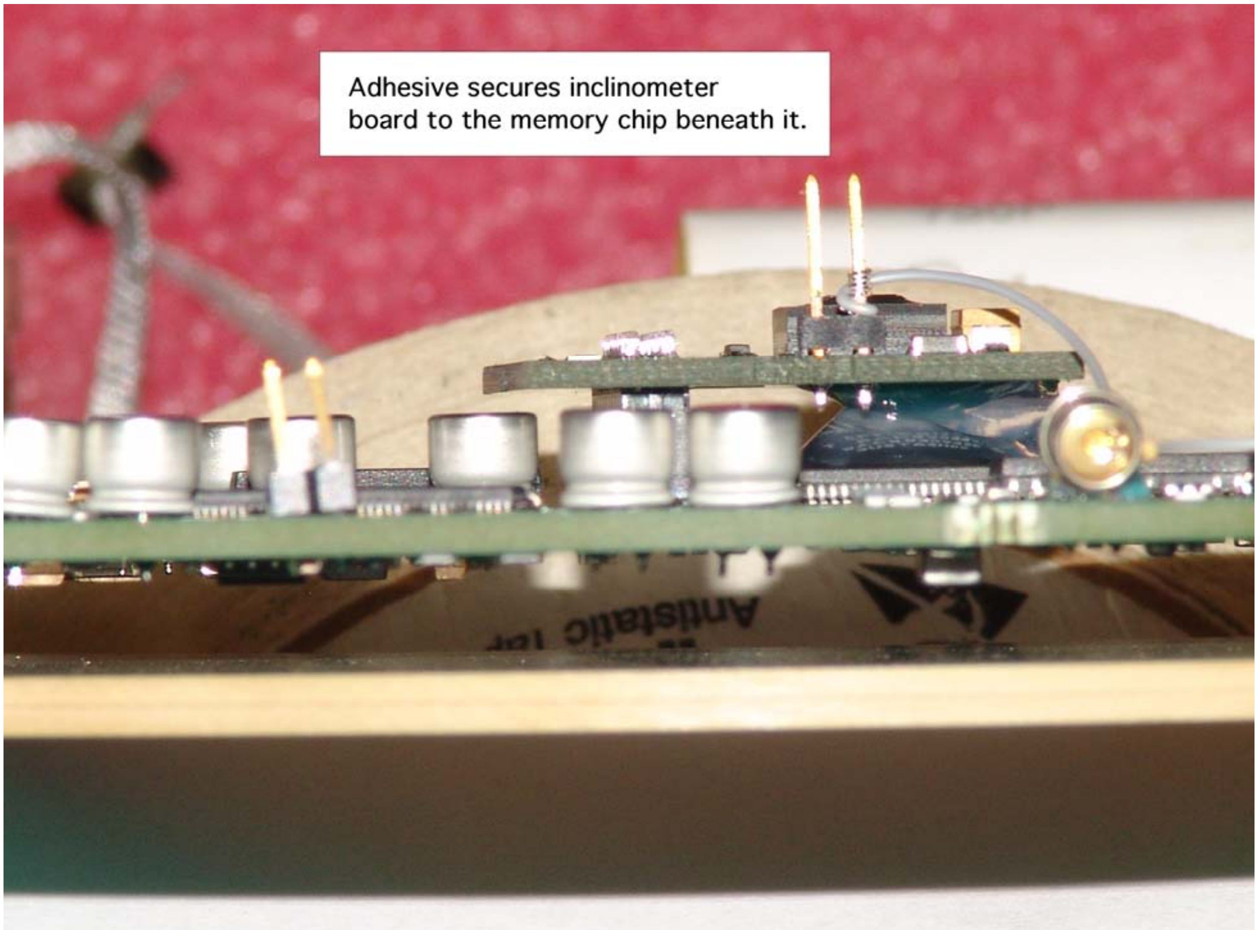


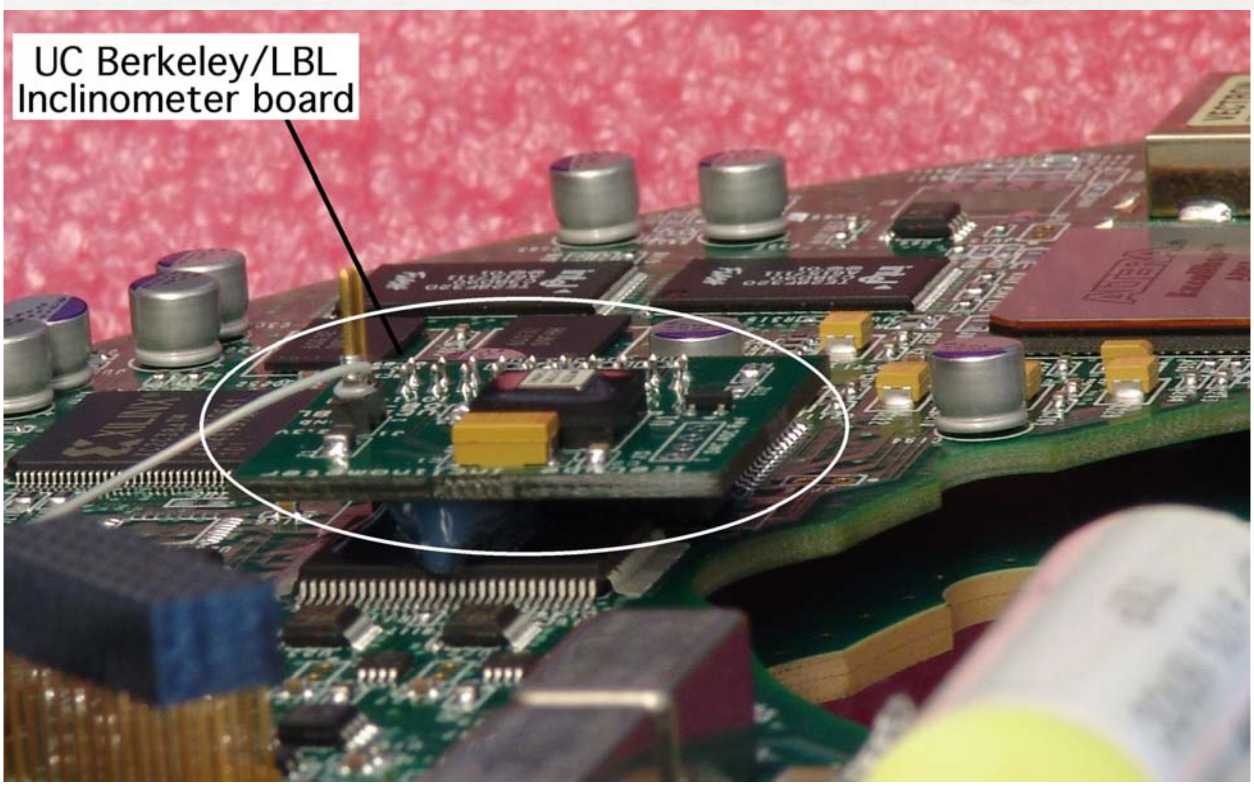
Connector JP14 with socket installed and underside of inclinometer circuit board.

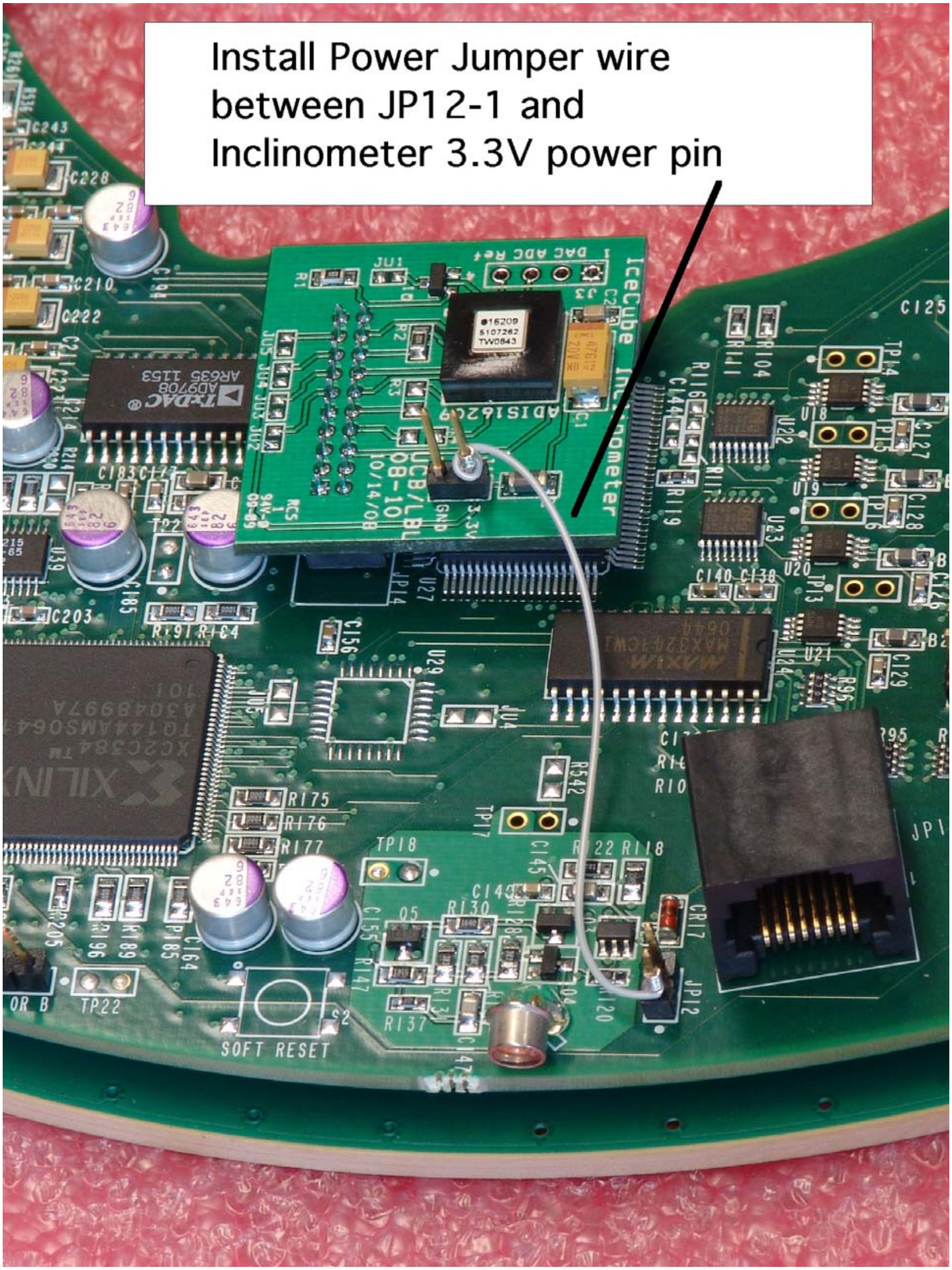
1) Apply a ~ 1 cm^3 blob of non-corrosive electronics grade RTV to the top of the config memory. This will hold the inclinometer board in place.



2) Plug the inclinometer board fully into the socket. Make certain that the adhesive adheres to both the config chip and the mezzanine card. Try to mount each card consistently and approximately level with the main board.


Adhesive secures inclinometer
board to the memory chip beneath it.


UC Berkeley/LBL
Inclinometer board



3) Install jumper from power pin on JP12 (lower pin, with dot) to the power pin on the inclinometer (right hand side, marked 3.3V).

4) (*Optional*) An SPI protocol serial interface module for the FPGA would need to be added to the Mainboard firmware in order to test the inclinometer installation prior to sealing the DOM. A few simple scripts below could then be used to confirm functionality.

Enable SPI interface:

```
#!/bin/bash

echo 'send "$30000 $90081060 !\r" expect "^>"' | se 02a
```

Query supply voltage:

```
#!/bin/bash

yinc=$(echo 'send "$0200 $90081090 ! 50000 usleep $0000 $90081090 ! 500
usleep $90081094 @ $3fff and . drop\r" expect "^>"' | se 02a | tr '\r' '\n' | grep '^[0-
9]'); echo "$yinc * 0.30518" | bc
```

Query temperature:

```
#!/bin/bash

yinc=$(echo 'send "$0a00 $90081090 ! 50000 usleep $0000 $90081090 ! 500
usleep $90081094 @ $3ffc and . drop\r" expect "^>"' | se 02a | tr '\r' '\n' | grep '^[0-
9]'); echo "((($yinc - 1278)/4)* -0.47) + 25" | bc
```

Query X inclination:

```
#!/bin/bash

yinc=$(echo 'send "$0c00 $90081090 ! 50000 usleep $0000 $90081090 ! 500
usleep $90081094 @ $3fff and . drop\r" expect "^>"' | se 02a | tr '\r' '\n' | grep '^[0-
9]'); echo "if ($yinc >= 2^13) (2^14 - 1 - $yinc) * -0.025 else $yinc * 0.025" | bc
```

Query Y inclination:

```
#!/bin/bash

yinc=$(echo 'send "$0e00 $90081090 ! 50000 usleep $0000 $90081090 ! 500
usleep $90081094 @ $3fff and . drop\r" expect "^>"' | se 02a | tr '\r' '\n' | grep '^[0-
9]'); echo "if ($yinc >= 2^13) (2^14 - 1 - $yinc) * -0.025 else $yinc * 0.025" | bc
```