Challenges of precise timing underwater

- No GPS!
- Limited power budget
- Size constraints
- Weight constraints

- On the bright side, temperature is often very stable

Timing requirements for Ocean Bottom Seismology

- Many independent instruments deployed in large arrays
- Timing arrival of seismic waves at each point across the array
- Desired timing accuracy is 1 millisecond
- Experiments range from a few weeks to one year in duration
- 1 ms / 365 days ≈ 3.2e-11
- Typical power budget ~ 1 W for entire system, <200mW for clock
- Many instruments required for an experiment, so unit cost is important

SISMTB Low-Power, High-Accuracy Time Base Module

- Manufactured by Seascan Inc. of Falmouth, MA
- 1.8 x 2.9 x 0.9 inches
- Microprocessor Compensated Crystal Oscillator
- In use for over a decade in hundreds of instruments

SISMTB Low-Power, High-Accuracy Time Base Module

- **Manufacturer's Specifications:**

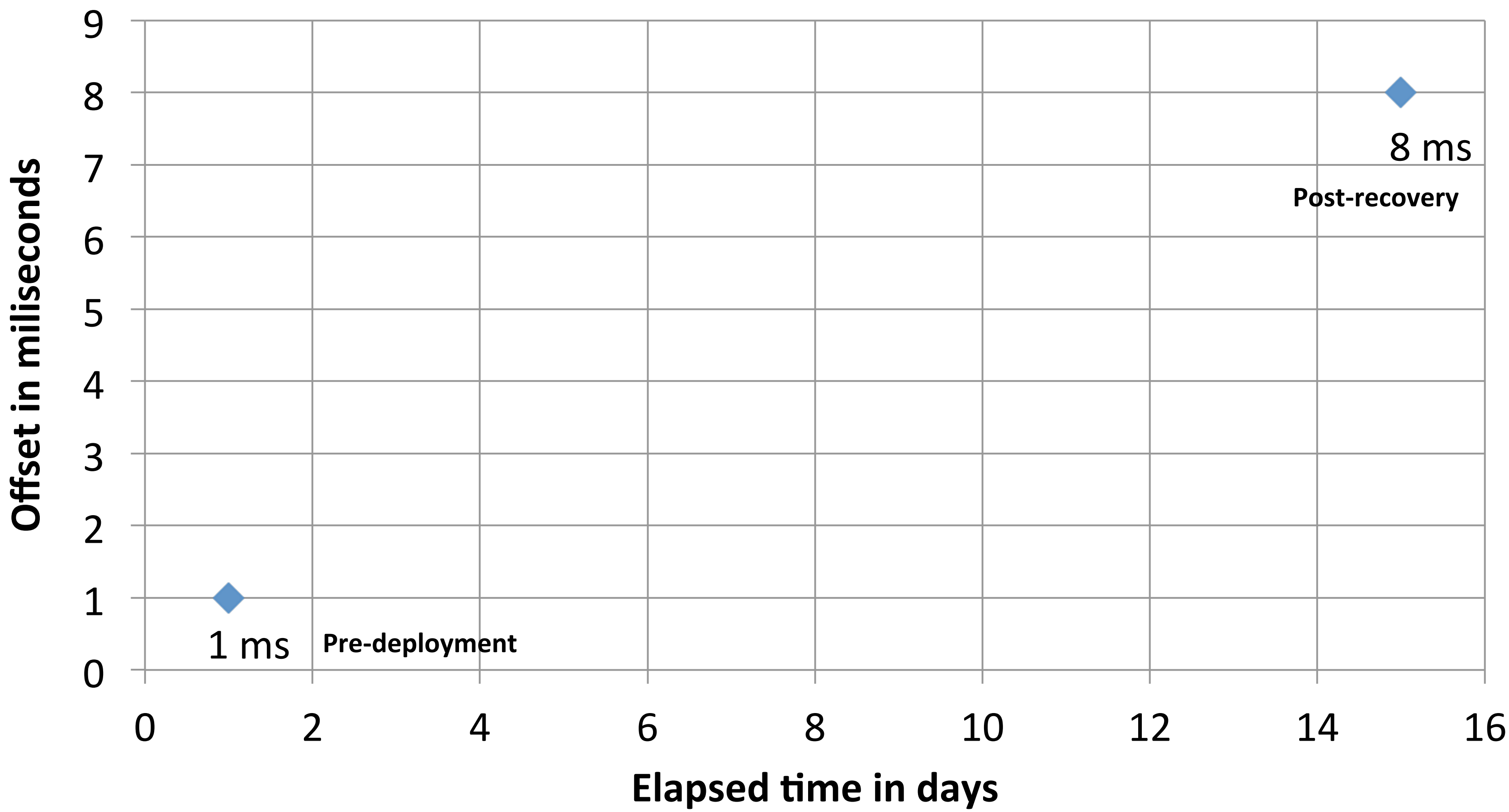
- 5e-8 long term stability (~4.3ms/day)
- -5 to 35 °C operating range
- 5mW typical power consumption
- 1 microsecond short term jitter
- 1 Hz and 125 Hz standard outputs
- Internal real time clock, ASCII interface
- High frequency PLL output available

Linear drift correction

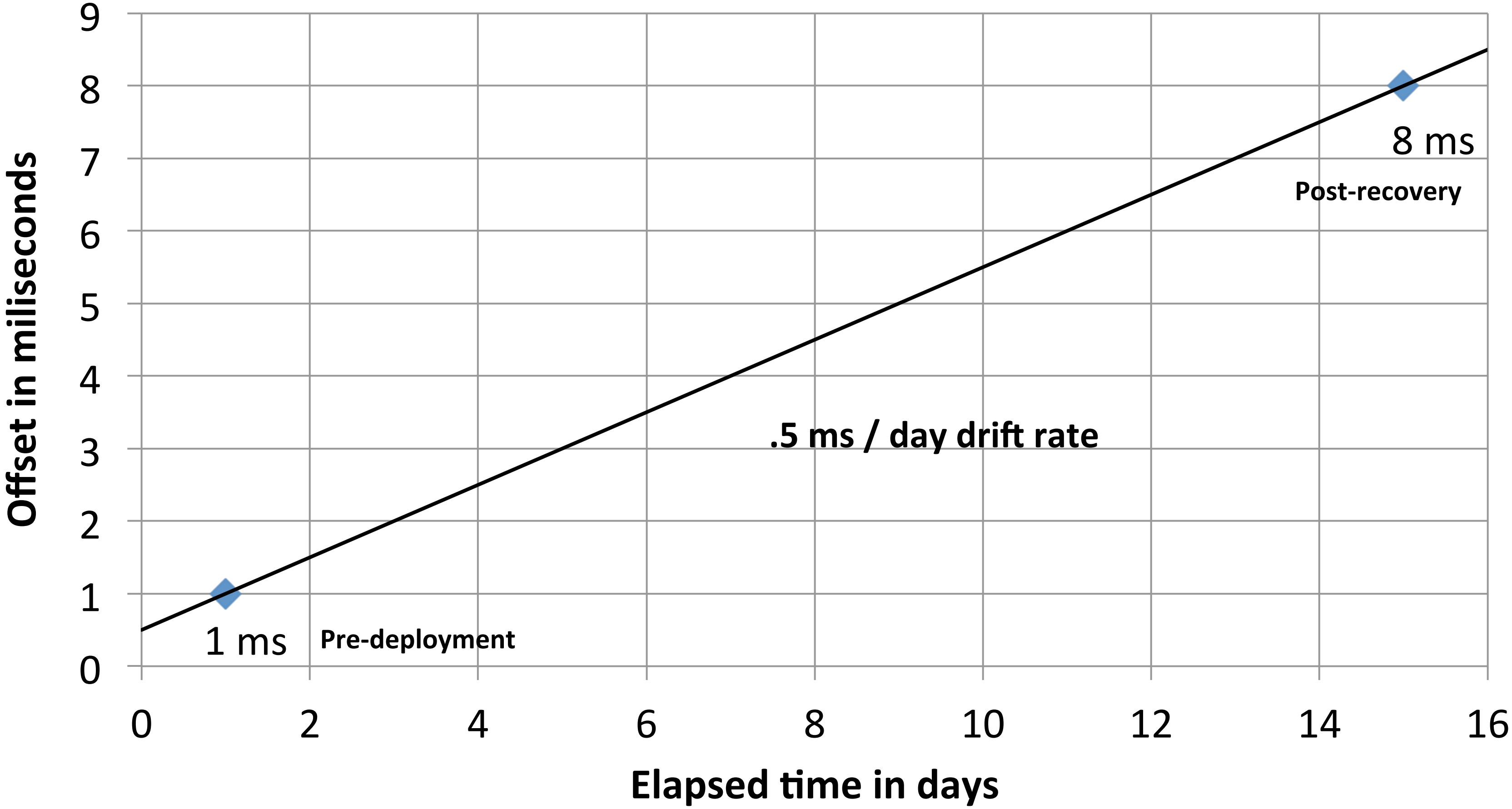
- **The best we can do to improve performance is a linear drift correction:**

- Largest contributors to frequency error are temperature and calibration error
- Temperature is constant in ocean bottom deployments
- Measure time offset between instrument clock and GPS before deployment and after recovery
- Assume frequency error to be constant
- Then clock phase error, or drift, is a linear function of time
- Re-sample data to correct for estimated drift throughout deployment

Linear drift correction example



Linear drift correction example

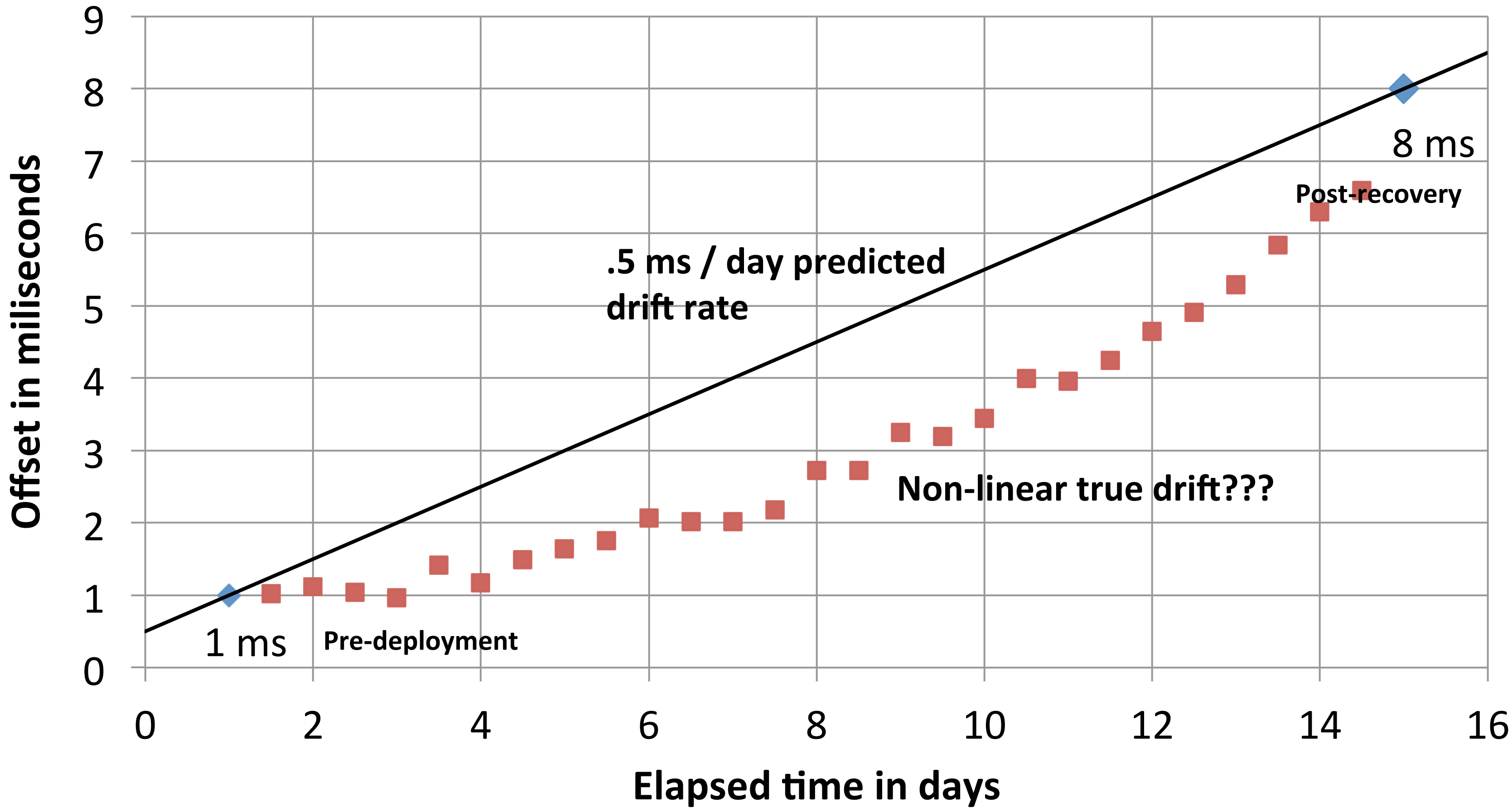


Linear drift correction problems

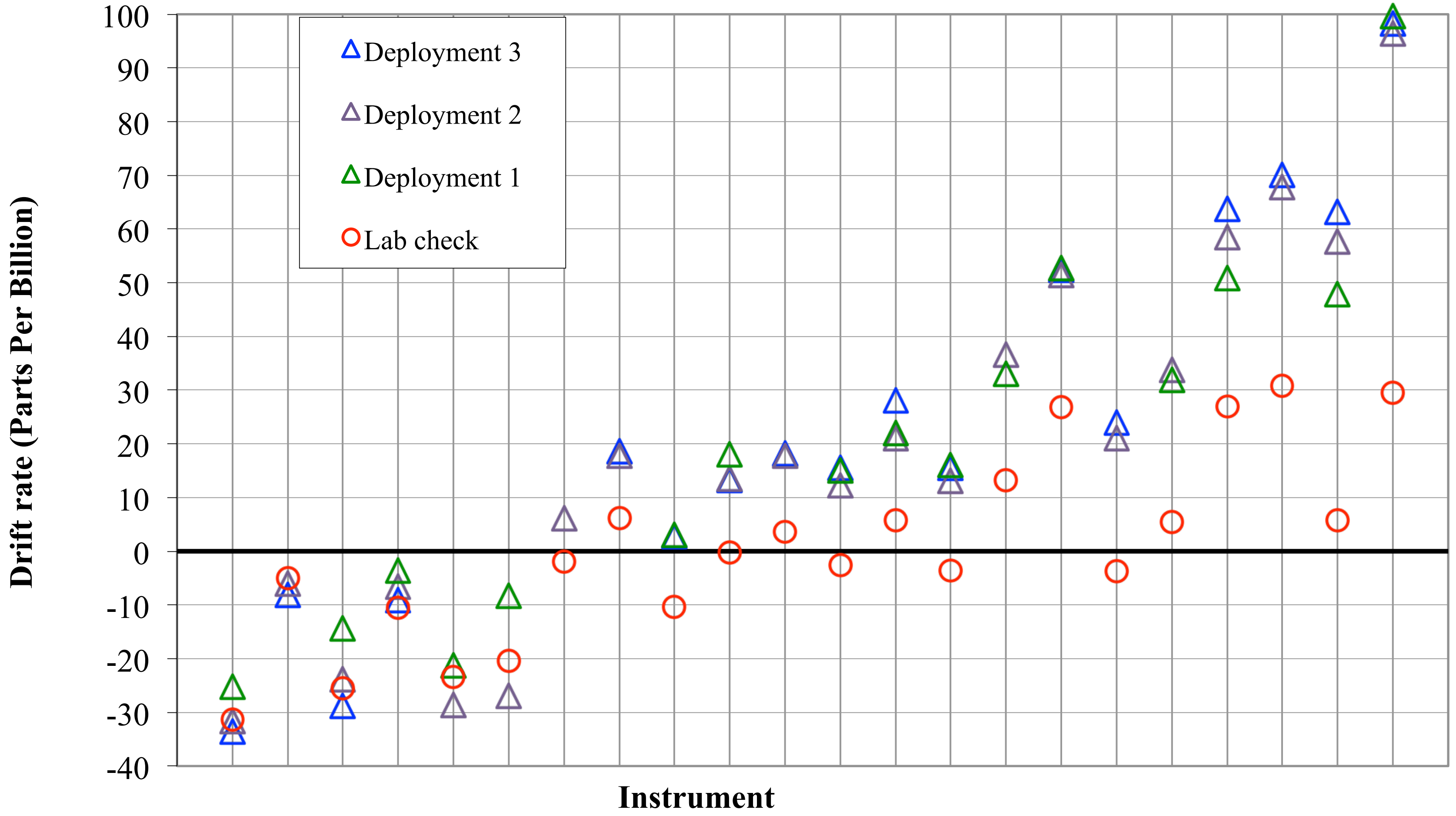
- Linear drift correction is effective, but not perfect
- Observed errors of 40 ms between neighboring instruments in 100 day deployments using noise correlation techniques
- Observed differences of ~10 ms between well-timed airgun shots roughly 2 weeks apart
- Aging causes frequency change / calibration error
- Other non-linear effects?

Linear drift correction example

What's really going on?

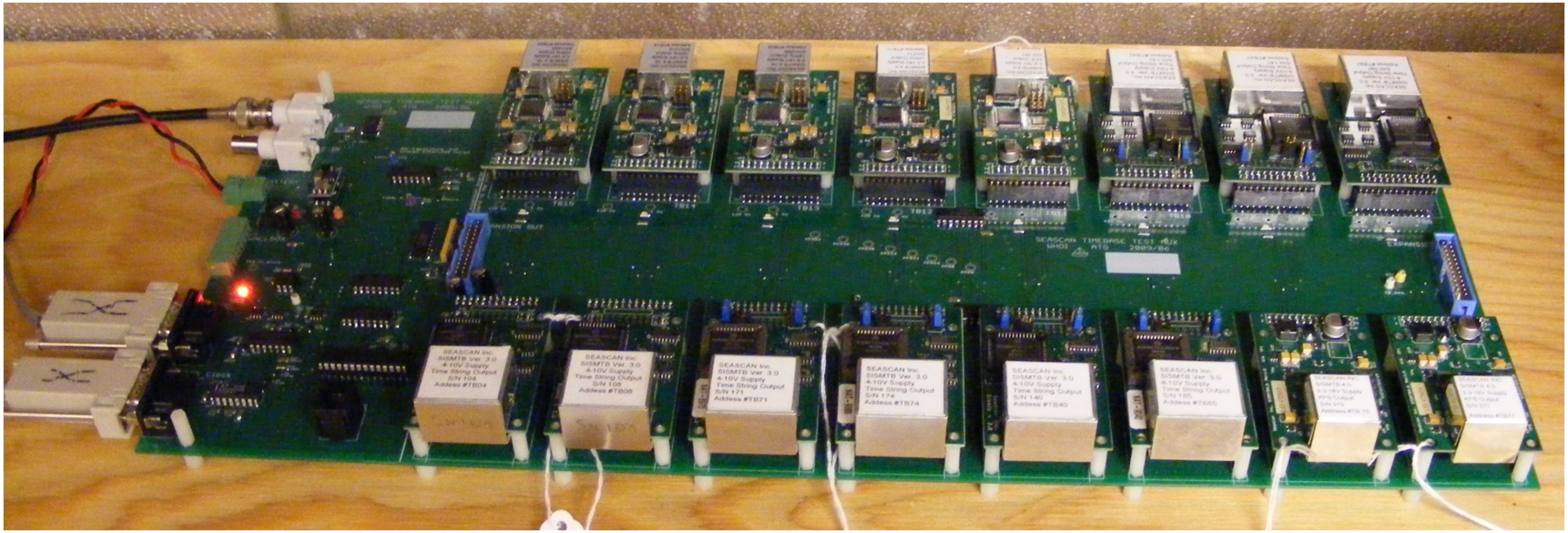


Testing clocks in the lab at room temperature is not enough!

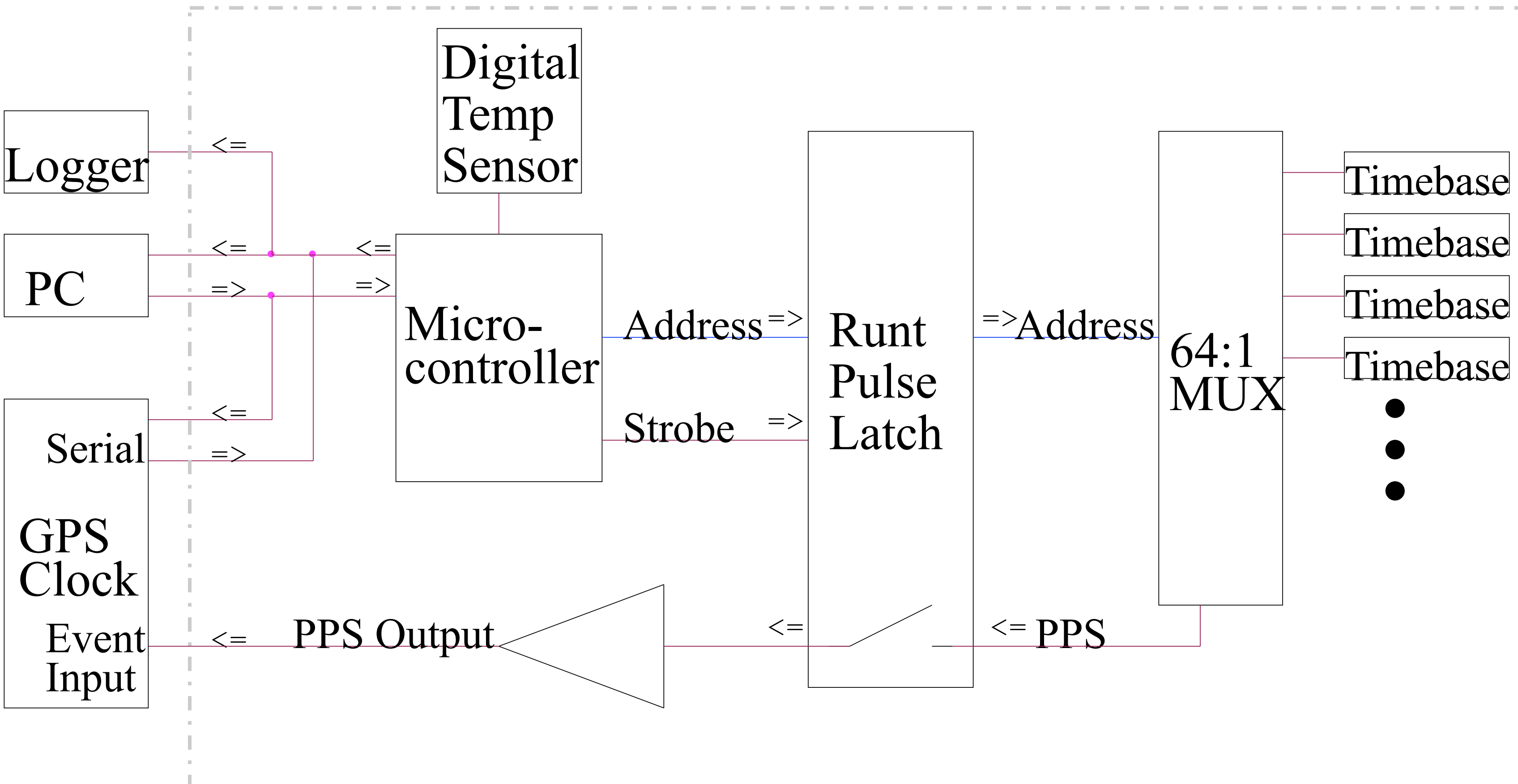


Seascan Multiplexer Board

- Lots of data from seafloor, but we wanted to monitor drift rates in real time for many clocks in a controlled environment
- Allows up to 64 Seascan Timebases to be tested simultaneously in a controlled temperature environment
- Temperature and offset of each clock measured vs. GPS and logged every minute
- Between 2009 and 2011 all of our Seascans were tested, with periodic retests since then
- Checking for calibration errors, temperature coefficient, effects of thermal shock, aging, and other non-linearities

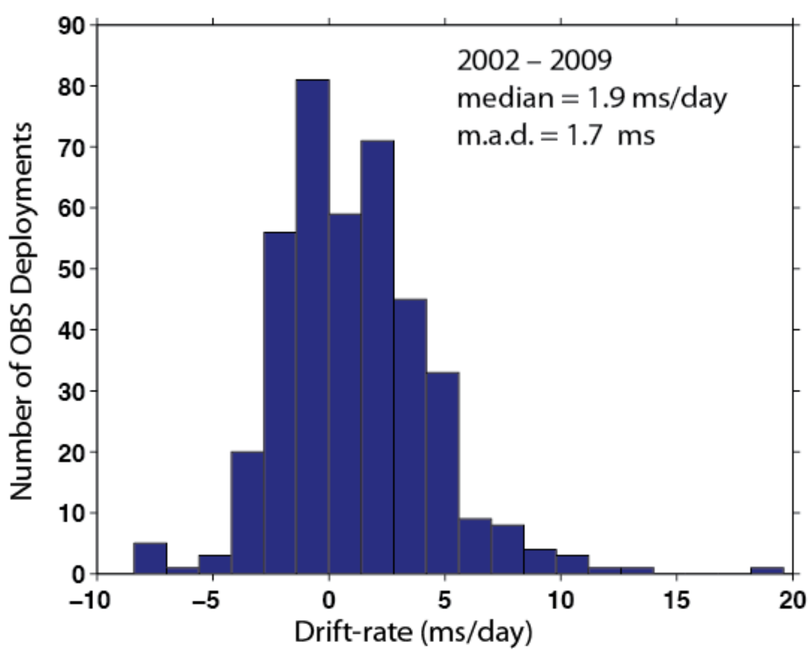


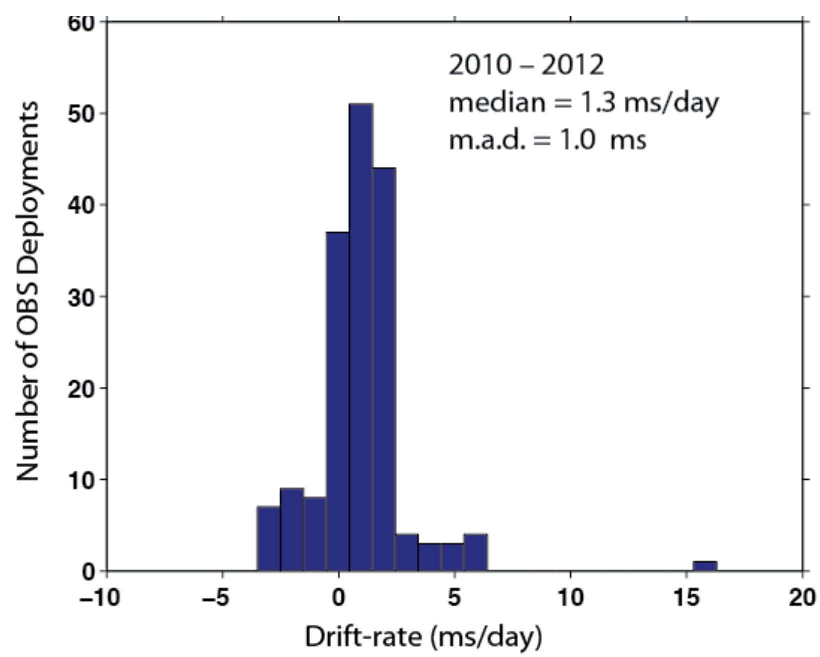
Seascan Multiplexer Block Diagram



Value of laboratory testing: Improved Seascan performance

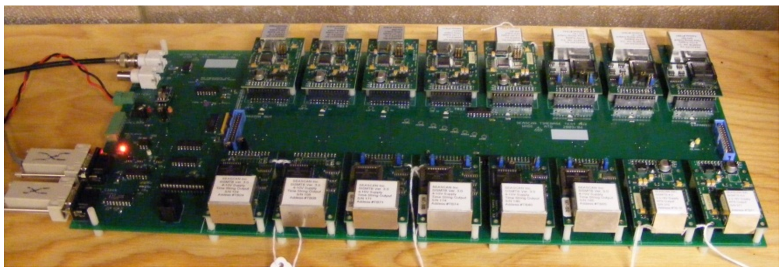
- Approx. 190 years total bottom time, 500 deployments
- Clocks are recalibrated after testing as necessary
- Most deployments within manufacturer's specs
- Histograms show significant improvements in calibration and temperature coefficients
- Not visible are effects of weeding out clocks with non-linearities

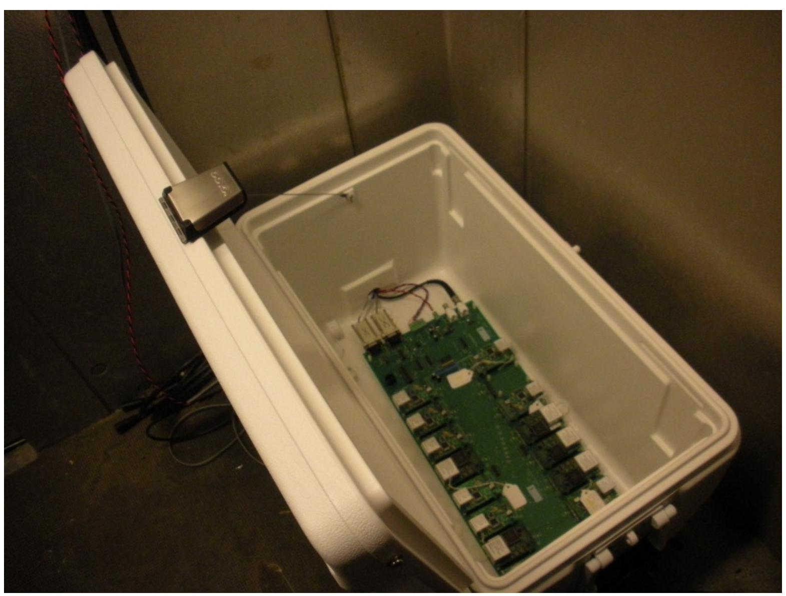


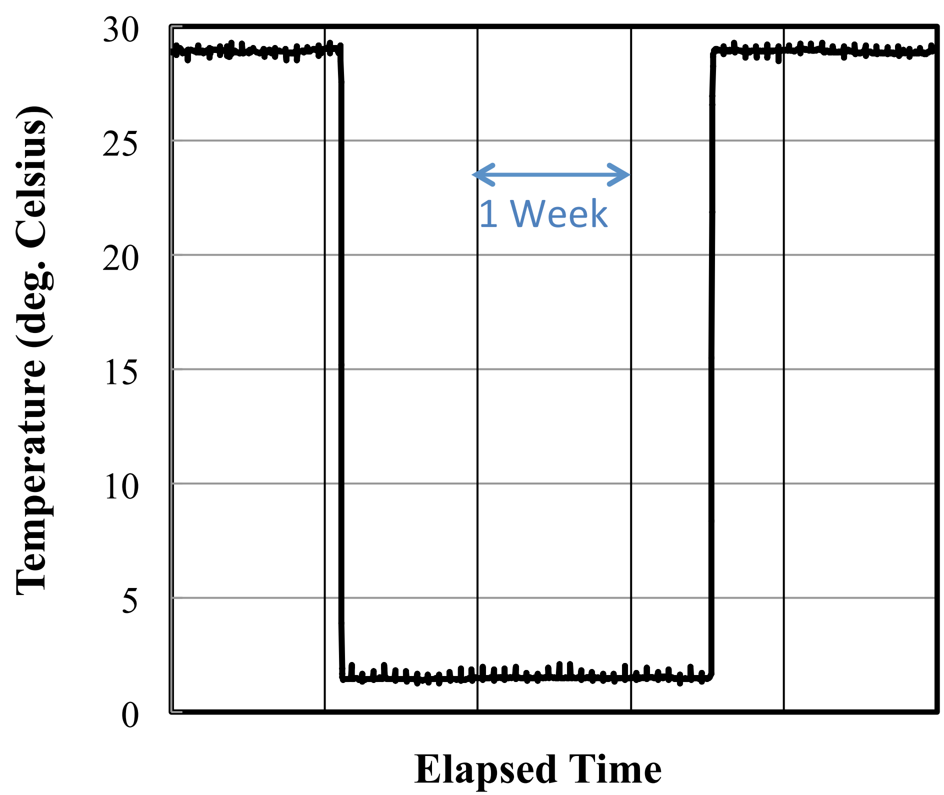


Lab testing protocol with Seascan multiplexer

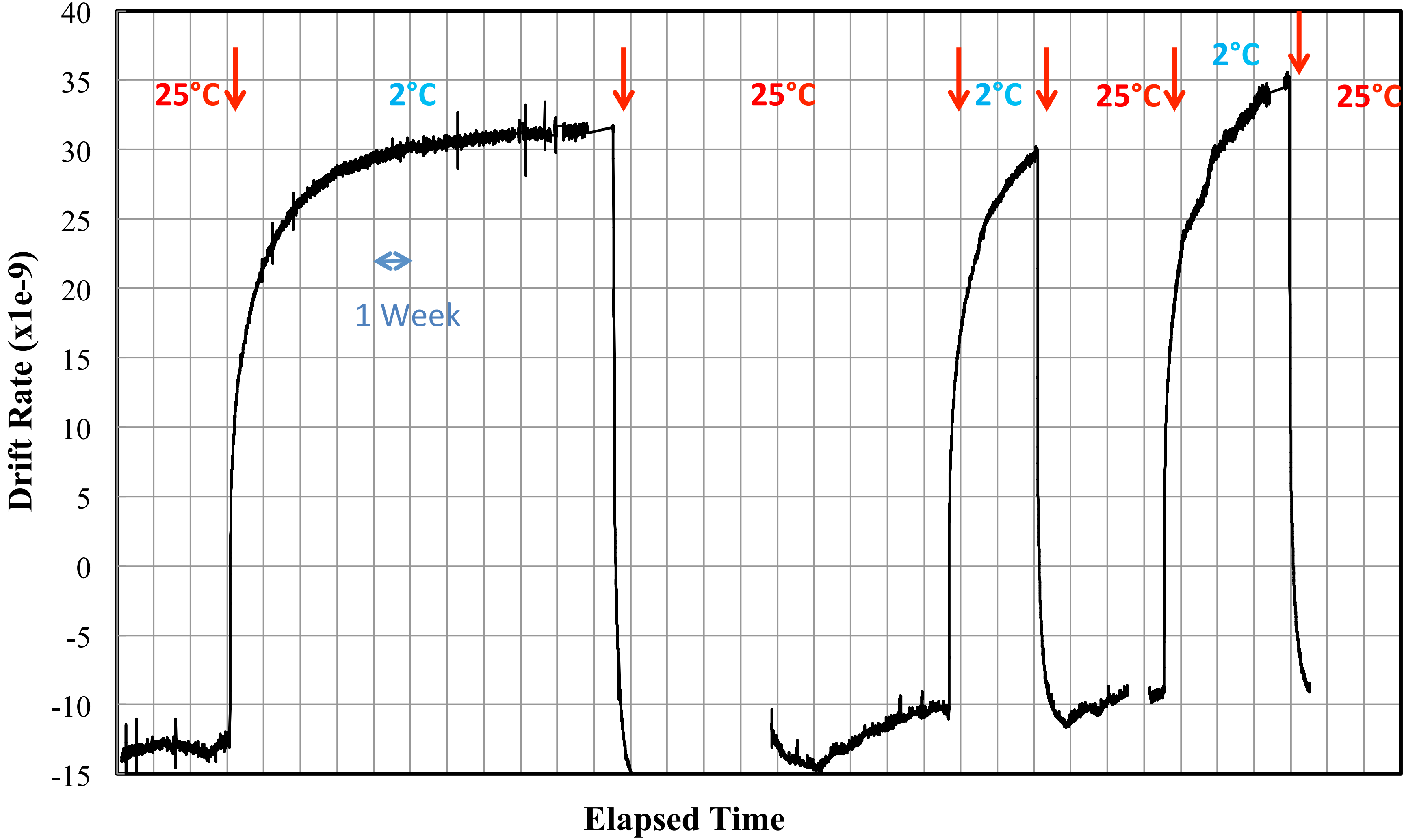
- Typical test cycle simulates a deployment
- Run at 25 °C for a few days, drop rapidly to 3 °C and hold for a few days to a few months, then return to 25 °C



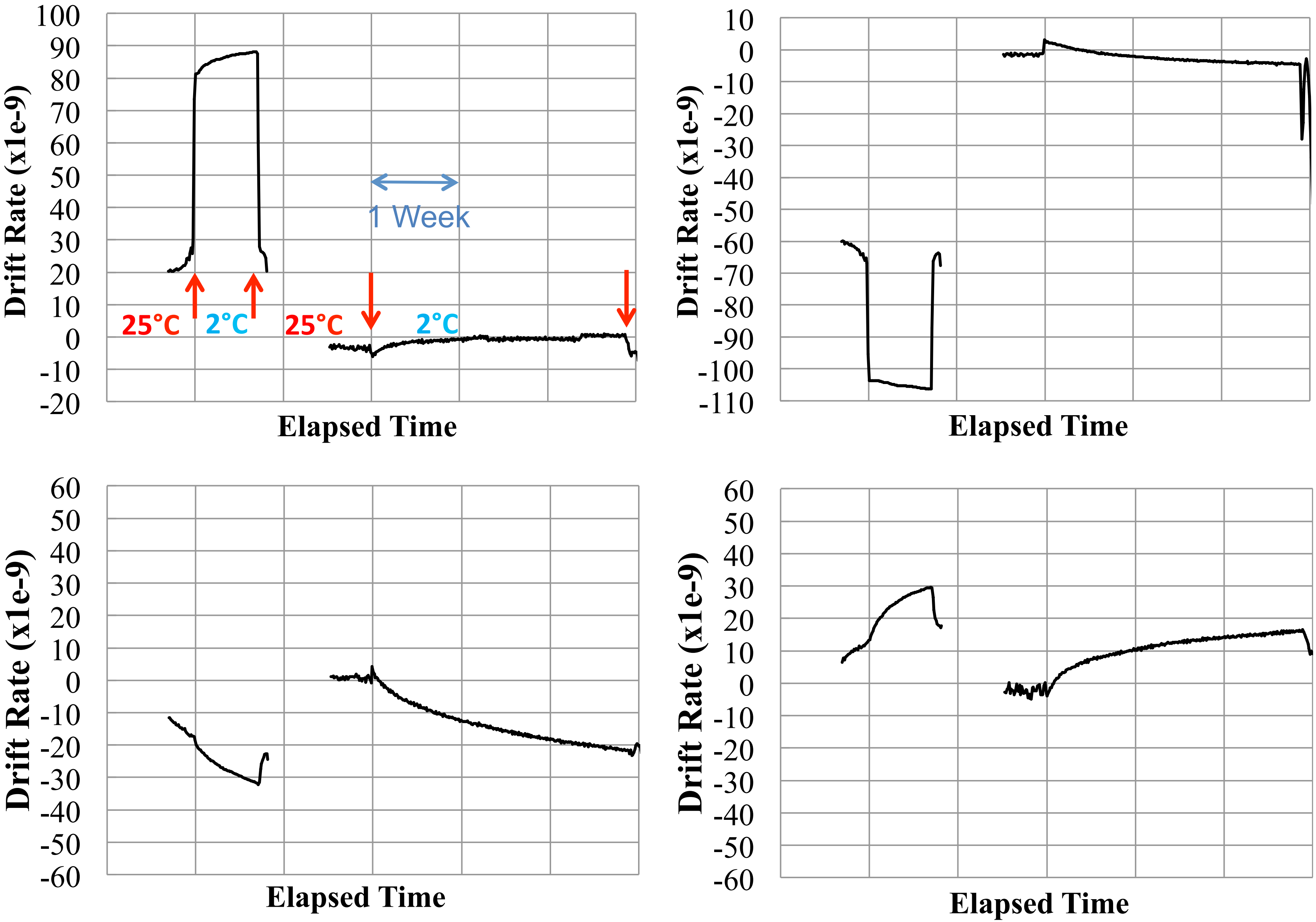




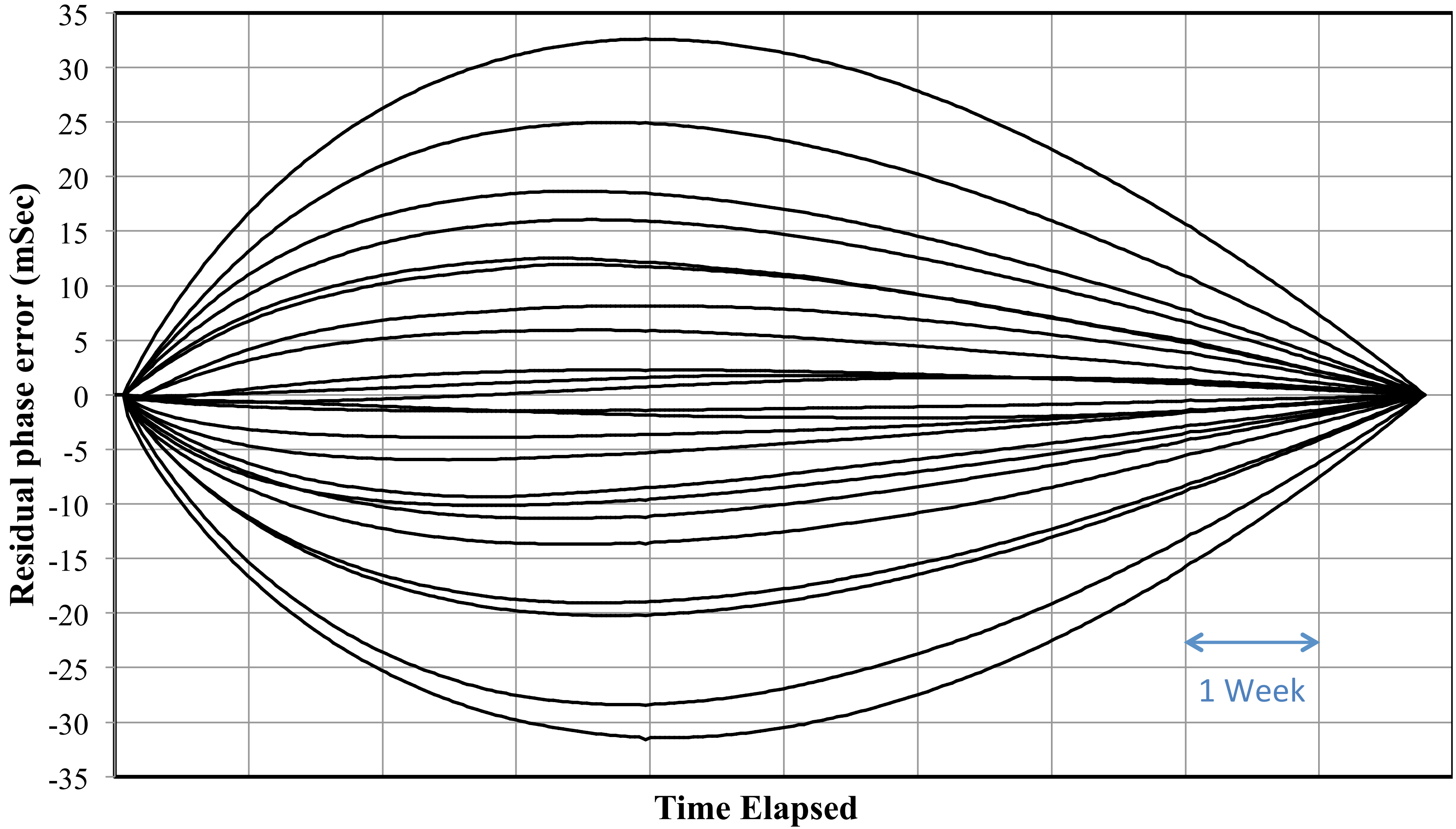
One time base showing temperature shock and other non-linearities on 3 separate tests



4 Time bases, before and after recalibration



23 Timebases, actual timing errors after linear drift correction in lab



Symmetricom Chip Scale Atomic Clock

- Seismology needs better performance than spec of Seascan
- Non-linear drift correction and careful testing and selection helps, but not good enough
- Symmetricom, Inc. of San Jose California developed world's first (and only) commercial chip scale atomic clock
- Constructed using MEMS technology
- Developed with DARPA grant
- Over an order of magnitude lower power than lowest power standard atomic clock
- Performance approaches that of standard Rubidium clock
- WHOI OBS lab received one of the first commercial prototypes

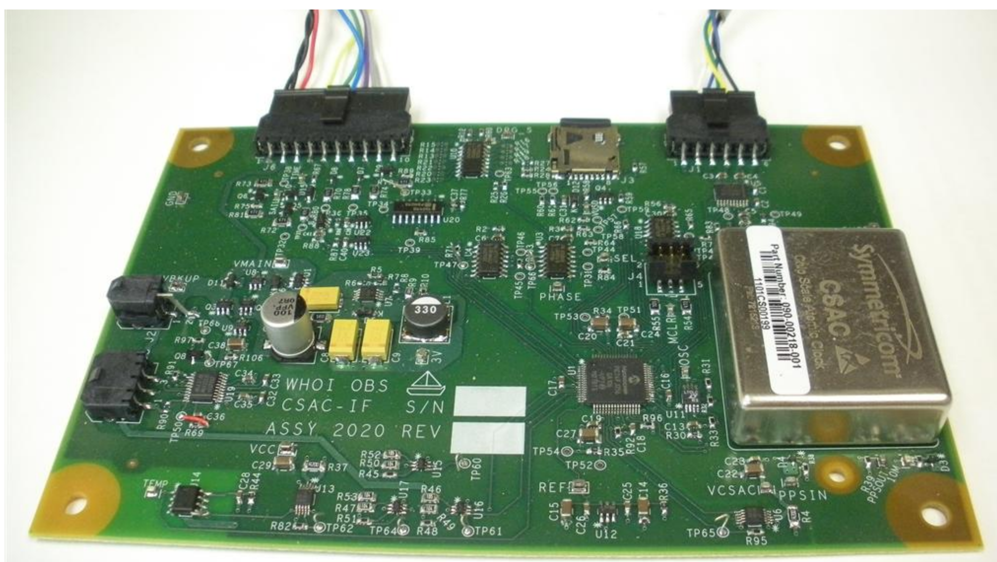
Symmetricom Chip Scale Atomic Clock

- Manufacturer's Specifications:

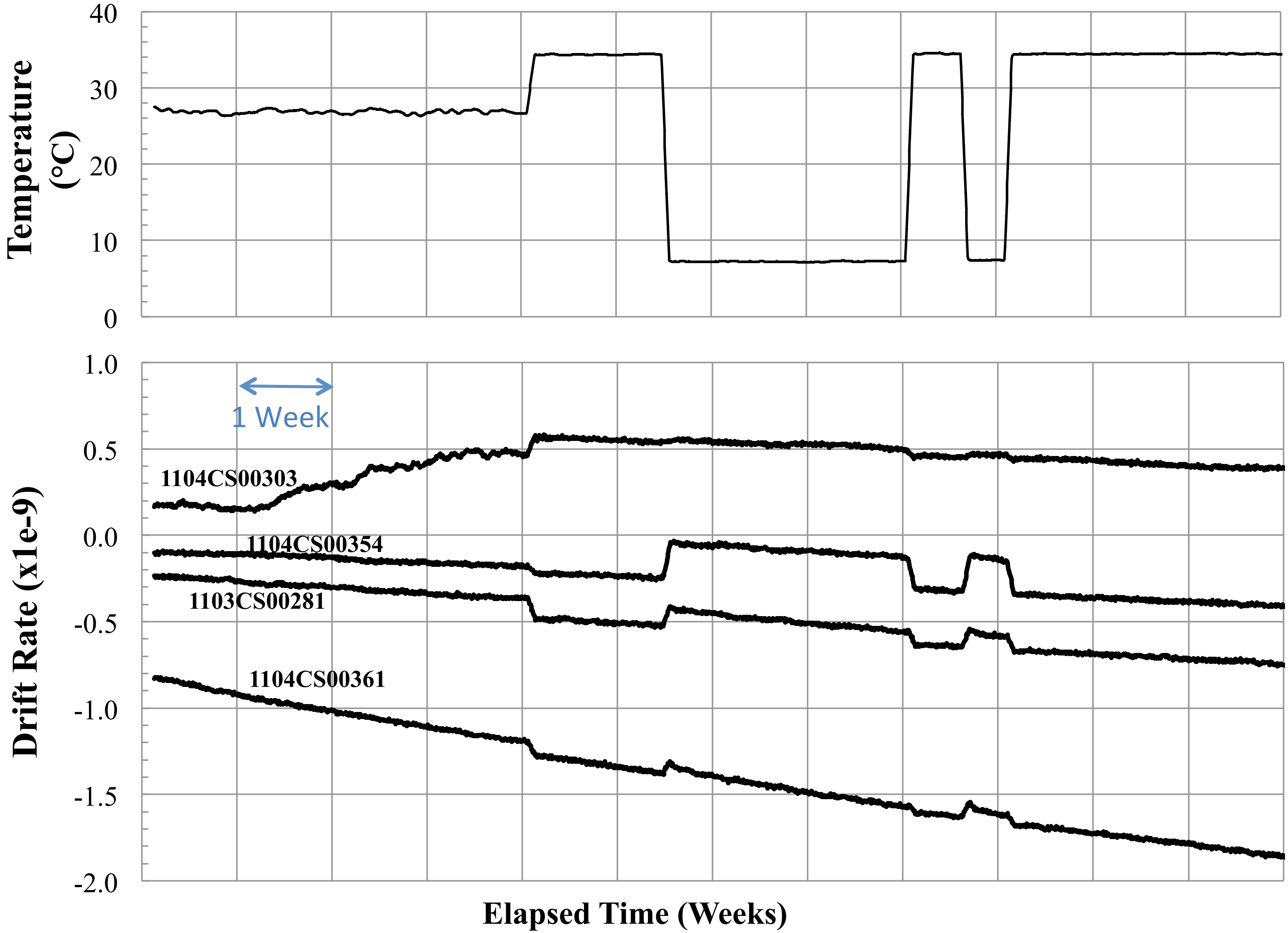
- Power consumption < 120 mW
- 1.6 x 1.39 x 0.45 inches
- Frequency accuracy +/- 5e-10 over temperature range
- Temperature range of -10 °C to +70 °C
- Jitter <1 nanosecond (Allan Deviation <1.5e-10 at 1 second, <1.5e-11 at 100 seconds)
- It provides 10 MHz and 1 Hz outputs.
- Internal "time of day" counter
- Can discipline to external 1 Hz reference

WHOI CSAC interface board

- Regulates power
- Maintains internal real time clock, set manually or by NMEA string
- **Simulates an NMEA output for Q330**
- **Built-in phase meter accurate to 100nS**
- Automatically **logs engineering values, including phase**
- Multiple input and output options (logic level and open collector pulse per second; RS-232 and open collector serial)
- Backup battery input



CSAC performance in lab over 3 month test



CSAC performance, first 6 month deployment

CSAC #	Deployment average drift rate (PPB)	Post recovery aging rate over last month (PPB/ month)	Notes
1104CS00304	-0.023	0.043	Deployed for ~6 months
1103CS00255	-0.049	0.014	Deployed for ~6 months
1104CS00379	0.071	0.090	Deployed for ~6 months
1104CS00362	0.107	0.038	Deployed for ~6 months
1106CS00594	0.110	0.155	Deployed for ~6 months
1104CS00372	-0.236	0.042	Deployed for ~6 months
1102CS00227	-0.256	-0.117	Deployed for ~6 months
1106CS00447	-0.367	-0.043	Deployed for ~6 months
1104CS00353	0.800	0.157	Not deployed
1102CS00239	**-1.170**	**-0.043**	Deployed for ~6 months
1103CS00300	**-1.243**	**-0.768**	Deployed for ~6 months
1101CS00199	**-1.562**	**-0.063**	Deployed for ~6 months
1102CS00209	**-2.634**	**-1.759**	Deployed for ~6 months
1101CS00193	**-3.542**	**0.020**	Deployed for ~6 months
1101CS00198	**-4.891**	-0.163	Not deployed. Vacuum leak!

Retrace and aging

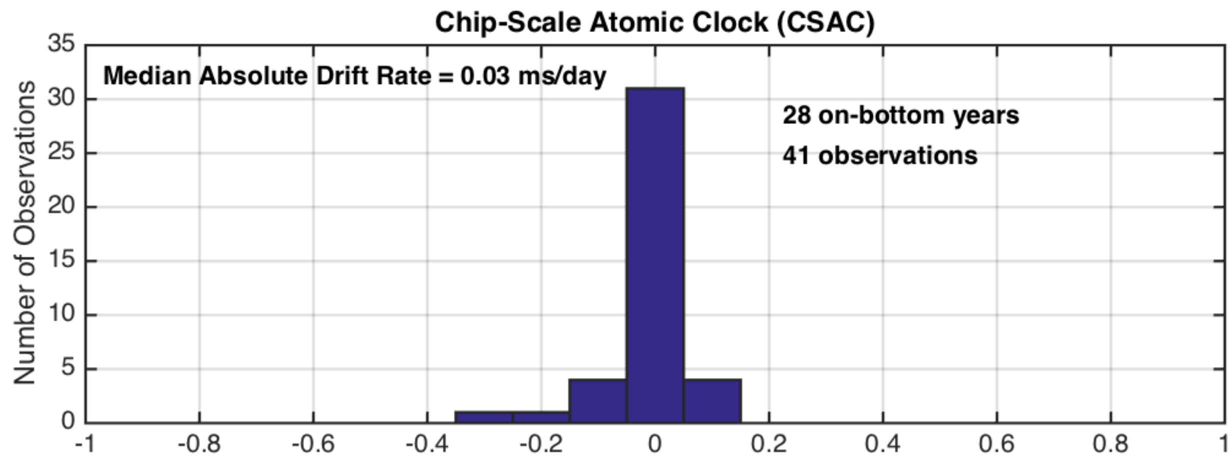
- Aging spec is <3e-10 per month, not to exceed <1e-9 per year
- Doesn't apply for first month after power up due to retrace
- Each time the CSAC is power cycled it will need to "age in" again
- We use battery to keep it powered during shipment

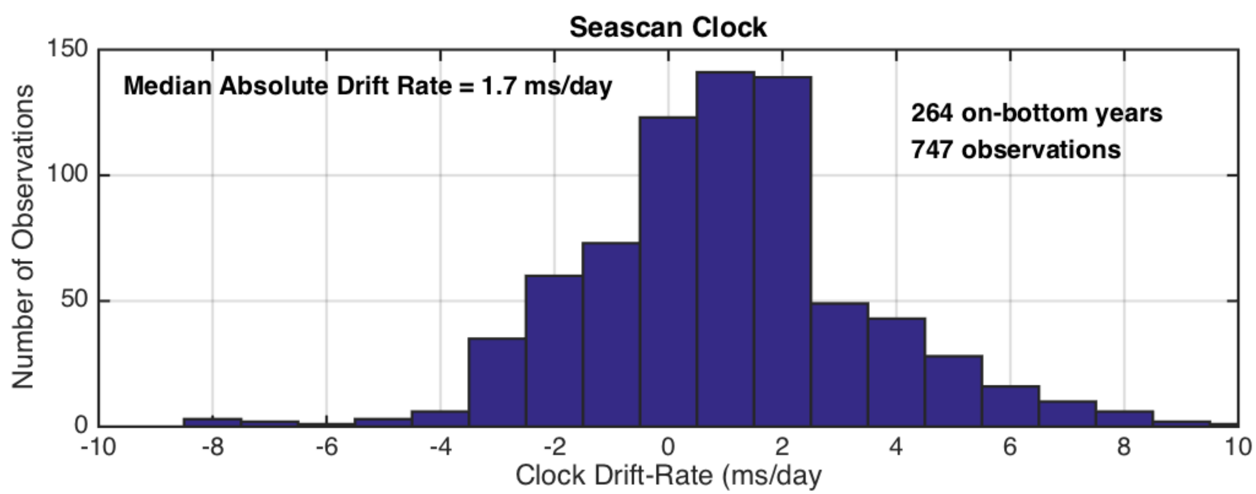
- High failure rate seen in year 1 of Cascadia initiative.
- We saw 3 failures out of 19 clocks tested
- Symmetricom claimed 0.5% failure rate overall
- All of the failures we saw were in very early production units
- Dramatic improvement in results seen after first Cascadia deployment

CSAC performance, Cascadia Years 1-3

	Cascadia year 1 (~6 mo)		Cascadia year 2 (~10 mo)		Cascadia year 3 (~10 mo)	
	Rate (ms/day)	**Drift (ms)**	Rate (ms/day)	**Drift (ms)**	Rate (ms/day)	**Drift (ms)**
1104CS00303	#N/A	#N/A	0.035	**10.02**	0.030	**8.47**
1103CS00255	-0.004	**-0.77**	-0.026	**-7.45**	-0.088	**-24.77**
1104CS00354	#N/A	#N/A	0.077	**22.01**	0.043	**12.06**
1106CS00447	-0.032	**-5.56**	-0.035	**-10.09**	-0.035	**-9.89**
1104CS00379	0.006	**1.07**	0.029	**8.17**	0.002	**0.51**
1102CS00239	**-0.101**	**-17.88**	-0.023	**-6.70**	-0.027	**-7.77**
1104CS00304	-0.002	**-0.36**	0.063	**17.93**	0.040	**11.33**
1101CS00193	**-0.326**	**-57.50**	-0.004	**-1.28**	0.000	**0.13**
1104CS00362	0.009	**1.57**	0.026	**7.32**	0.018	**6.02**
1104CS00353	0.069	**9.26**	0.048	**13.79**	0.012	**3.47**
1106CS00594	0.011	**1.81**	0.052	**14.88**	0.021	**5.88**
1104CS00372	-0.020	**-3.61**	-0.035	**-12.27**	-0.020	**-5.35**
1103CS00281	#N/A	#N/A	0.072	**20.61**	0.050	**14.04**
1102CS00227	-0.022	**-3.88**	0.004	**1.10**	0.001	**0.16**
CSAC Max:	0.069	**9.26**	0.077	**22.01**	0.050	**14.04**
CSAC Min:	-0.326	**-57.50**	-0.035	**-12.27**	-0.088	**-24.77**
CSAC Avg (Abs):	0.055	**9.39**	0.038	**10.97**	0.028	**7.85**
Seascan Max:	1.720	**305.23**	1.661	**473.27**	1.780	**509.52**
Seascan Min:	-0.300	**-54.27**	-0.388	**-111.88**	-0.330	**-97.63**
Seascan Avg (Abs):	0.900	**158.46**	0.858	**245.18**	0.930	**263.75**

Historical WHOI clock performance

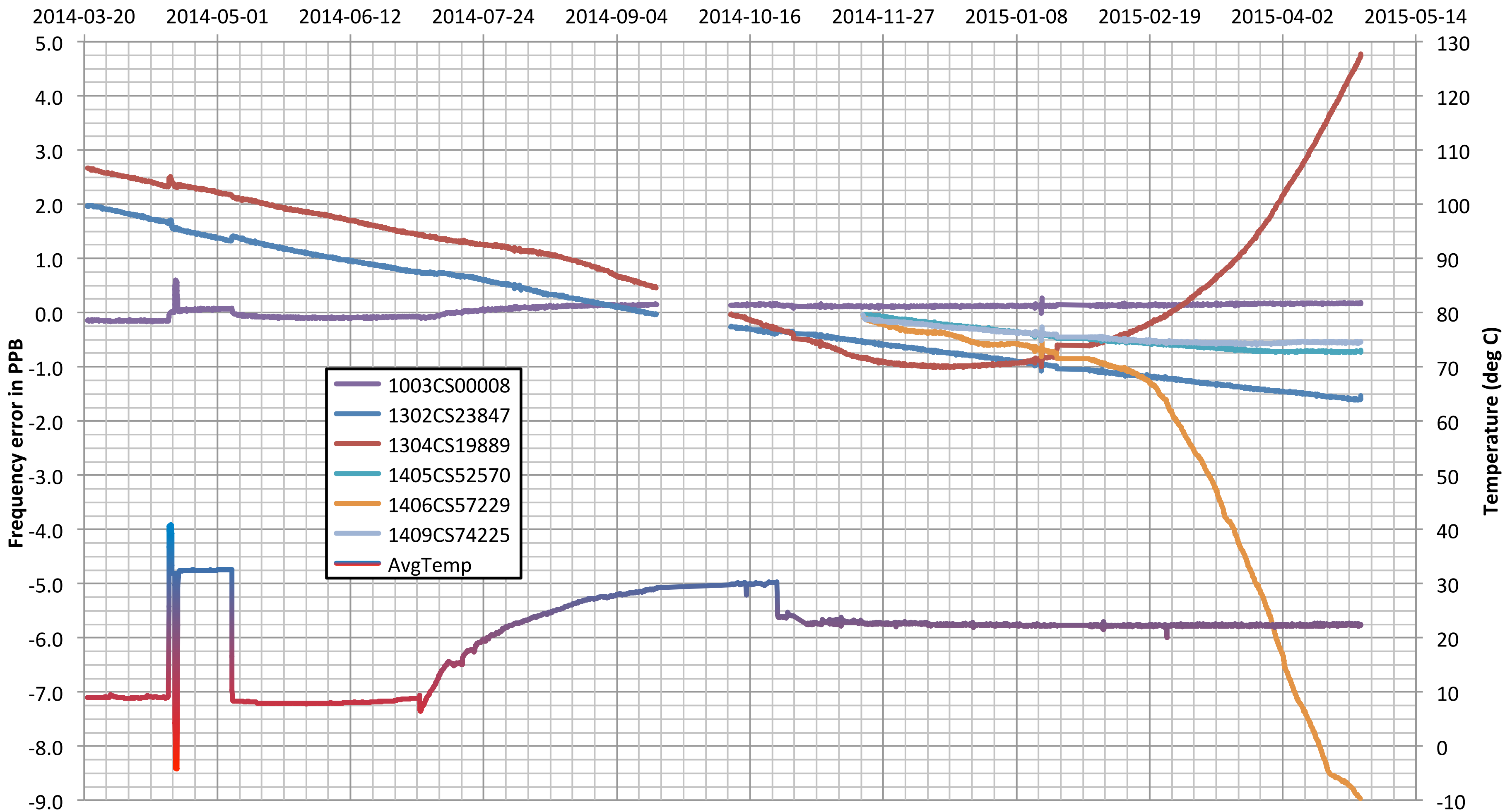




Current status of CSAC production

- Symmetricom has been purchased by Microsemi
- Serious production issues (likely not related to Microsemi acquisition)
- CSACs currently sold only under waiver reducing max storage and operating temperature to 35 deg C, and increasing aging spec by factor of 10
- Significant failure rate due to loss of vacuum, exacerbated by elevated temperatures
- Production issues began sometime around 2012 or 2013
- Watch for increases in HeatP in status for indication vacuum leak – should be around 10 to 15 mW; cannot maintain temperature above ~35mW
- Fixes are being implemented, but improved parts will not be available until December 2015 at the earliest

Six CSACs being tested at WHOI



Summary

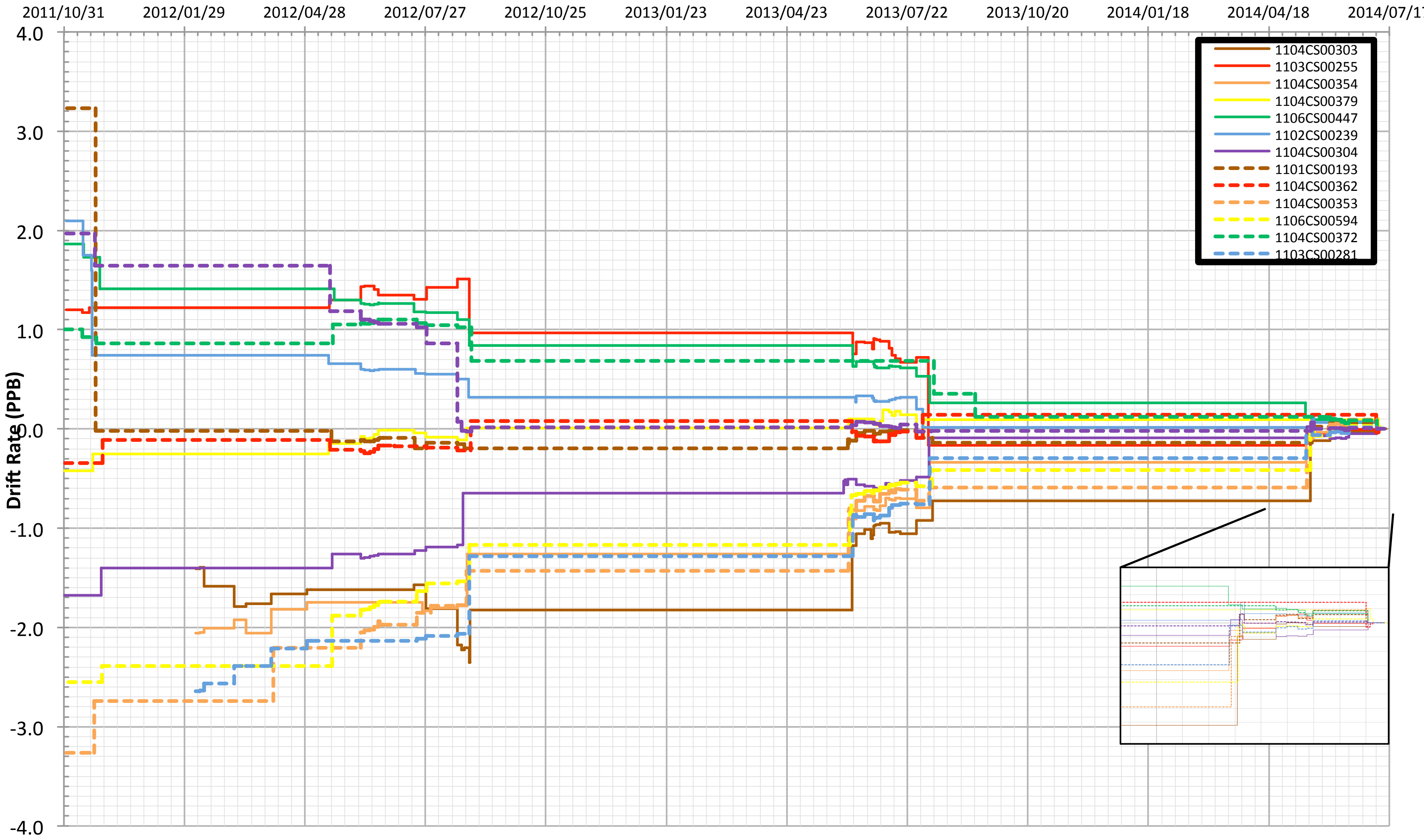
Seascan Timebase

- 5e-8 stability
- ~1 microsecond jitter
- -5 to 35 °C
- Return to factory for recalibration
- **5mW**
- *Good enough for many applications*
- *Important to understand non-linearities*

Symmetricom CSAC

- **<1e-9 stability (temperature, magnetics, supply voltage)**
- **~1 nanosecond jitter**
- **-10 to 75 °C**
- **Discipline to GPS**
- 120mW
- *Significantly better performance at cost of higher power*
- *Important to understand aging effects*

Cascadia CSAC measured drift rates



Summary of results from Seascan testing

- After years in service, many clocks had large static frequency errors and incorrect temperature coefficients near to or exceeding the 5e-8 spec.
- Factory recalibration corrected these problems; however, assuming a constant temperature on the seafloor, these problems will be corrected by linear drift corrections anyway.
- Most clocks show some long term change in frequency error after a temperature change. This can represent a significant non-linear error, which cannot be easily corrected.
- The shape of the frequency error curve after a change in temperature for each clock is consistent.
- Recalibration does not change the shape of the frequency error curve.
- Other effects such as aging and random variations observed, but generally small compared to temperature shock.