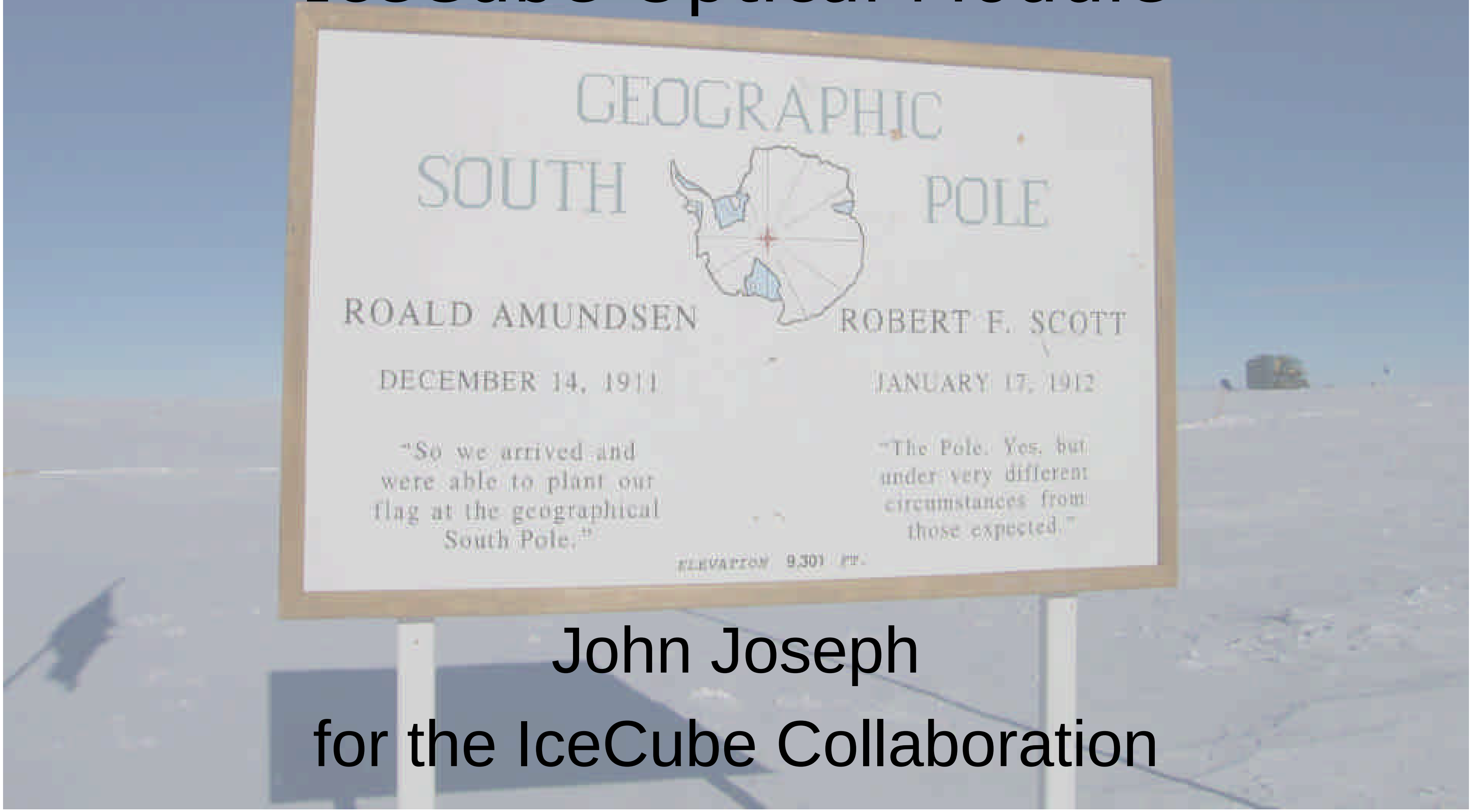
Electronics in the Polar Ice:

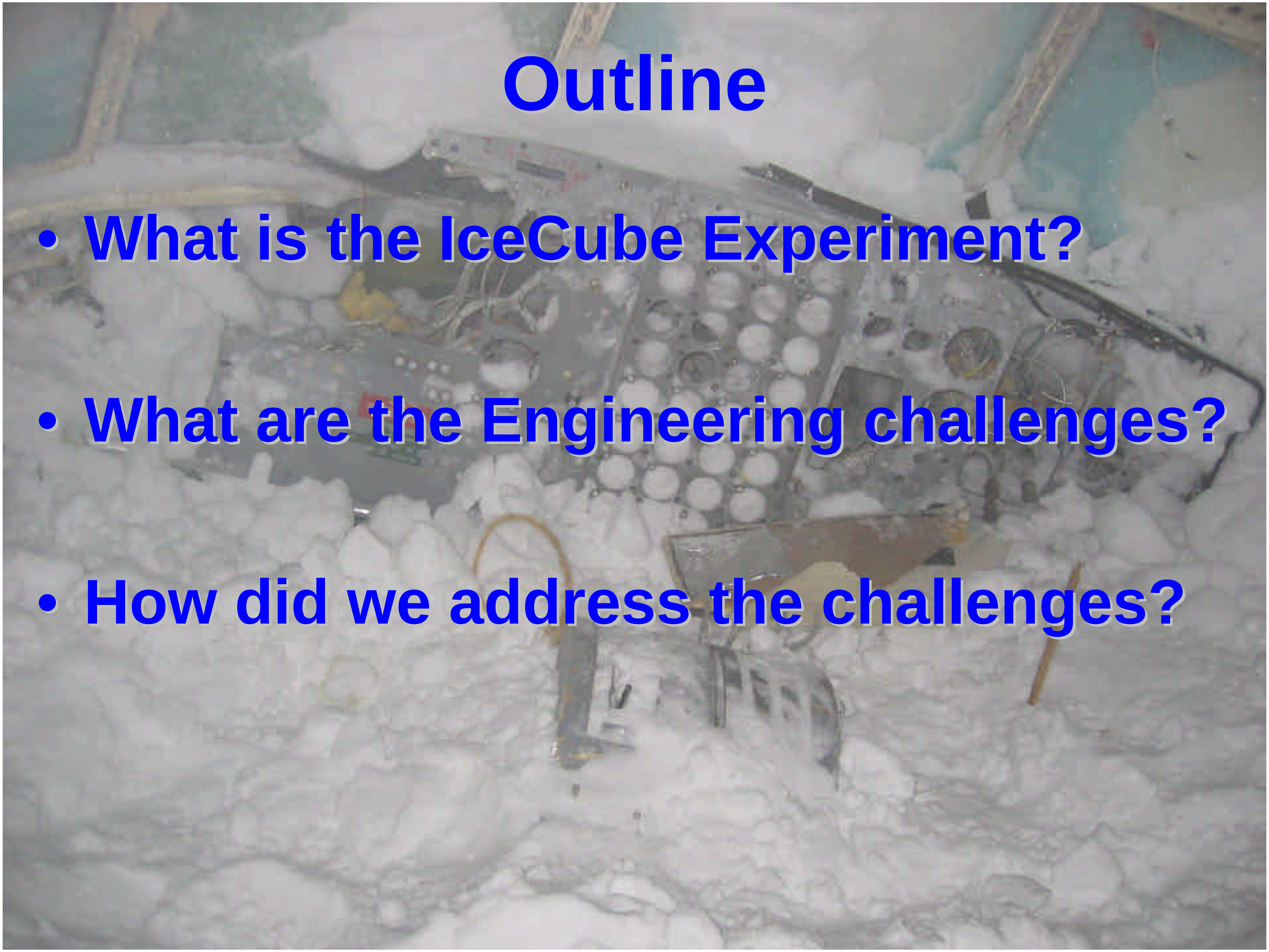
The Engineering Challenges of the IceCube Optical Module



John Joseph

for the IceCube Collaboration

Outline



- **What is the IceCube Experiment?**
- **What are the Engineering challenges?**
- **How did we address the challenges?**

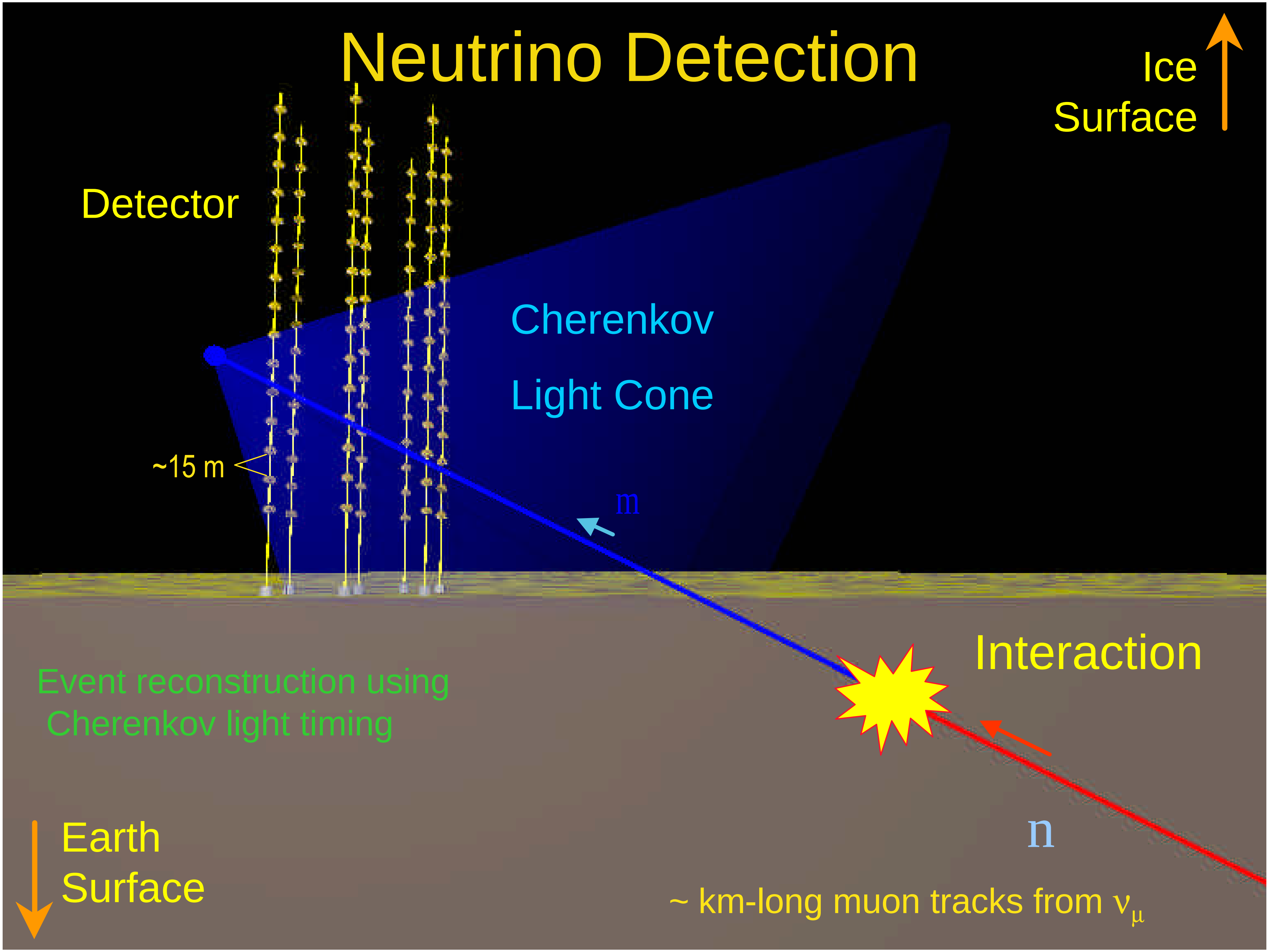
What is IceCube?

- Giant Cherenkov detector built into 1 billion tons of ice
  - Mission: To detect all types of Neutrinos at energies from 10^{11} eV to 10^{20} eV, and low energy ν's from supernovae
- Instrumented volume ➔ 1 kilometer cubed
  - A larger detector increases the probability of “seeing” Neutrinos
  - High energy muons have long ranges
    - Allows larger sample of the muon track

What is IceCube?

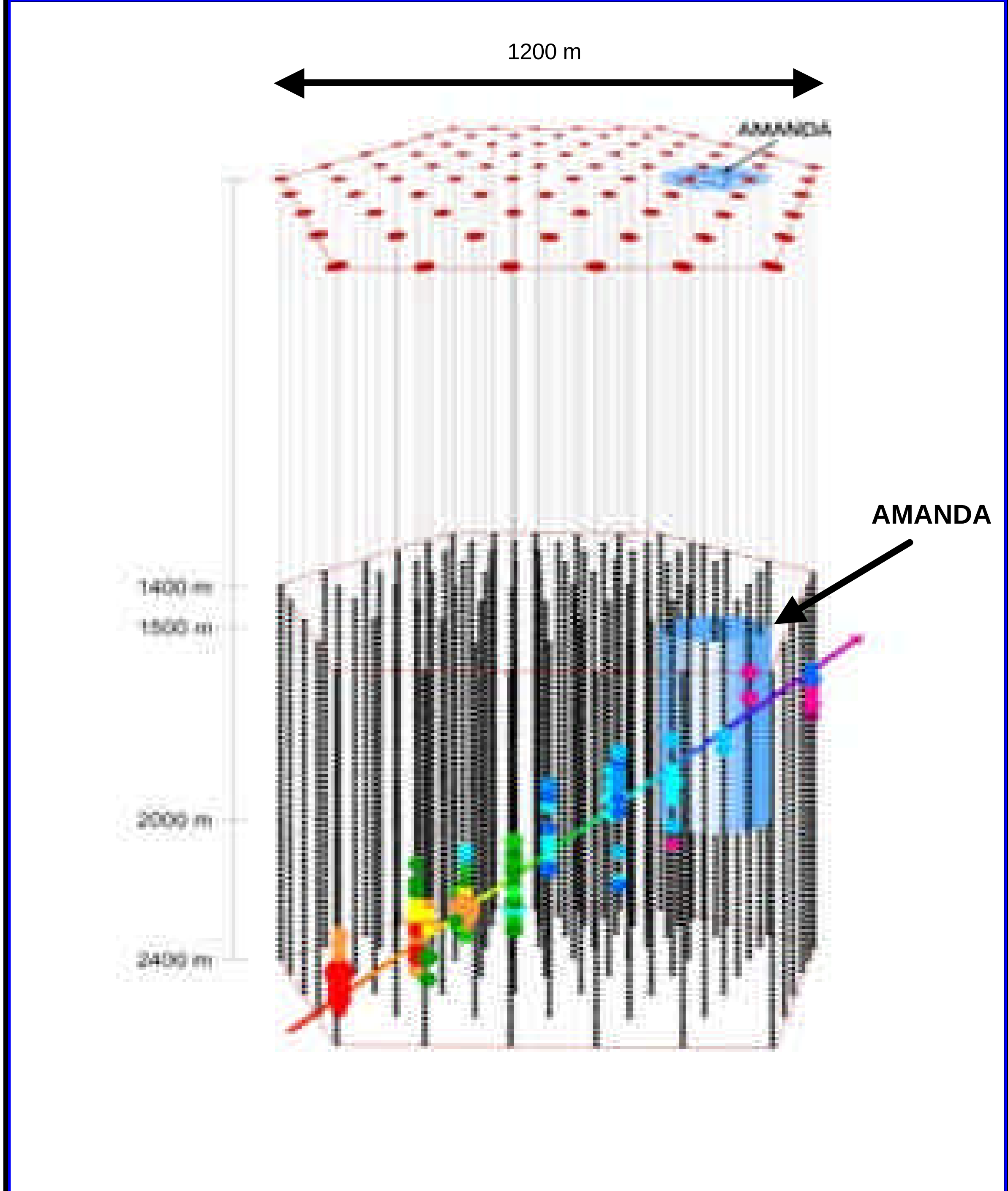
- Detector modules point down to use the Earth as a muon filter
  - Interesting interactions are from Neutrinos coming through the Earth

- Construction at the South Pole
  - Large volume and shielding only found in deep water or ice
  - 10,000 foot depth of pure, clear ice
  - Experiments in deep water, believe it or not, are even more difficult to build
  - History: AMANDA already in operation

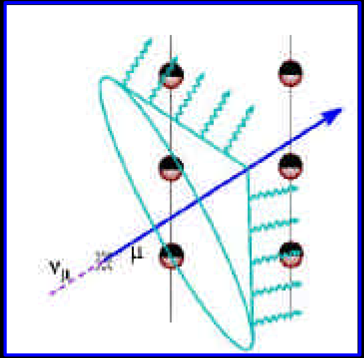

Neutrino Detection
Ice
Surface
Detector
Cherenkov
Light Cone
~15 m
m
Interaction
Event reconstruction using
Cherenkov light timing
n
Earth
Surface
~ km-long muon tracks from ν_μ

IceCube

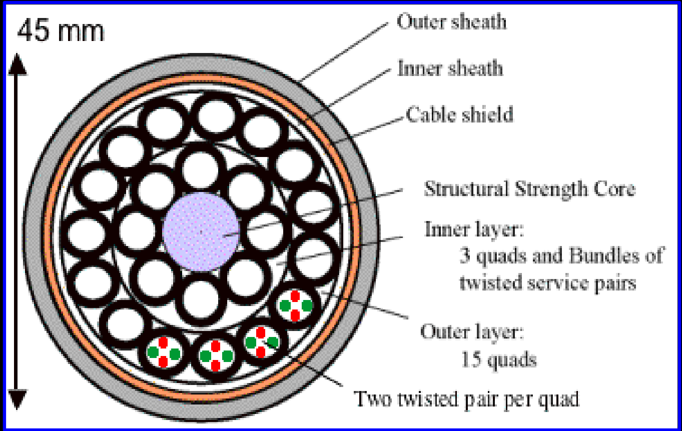
Detector Array



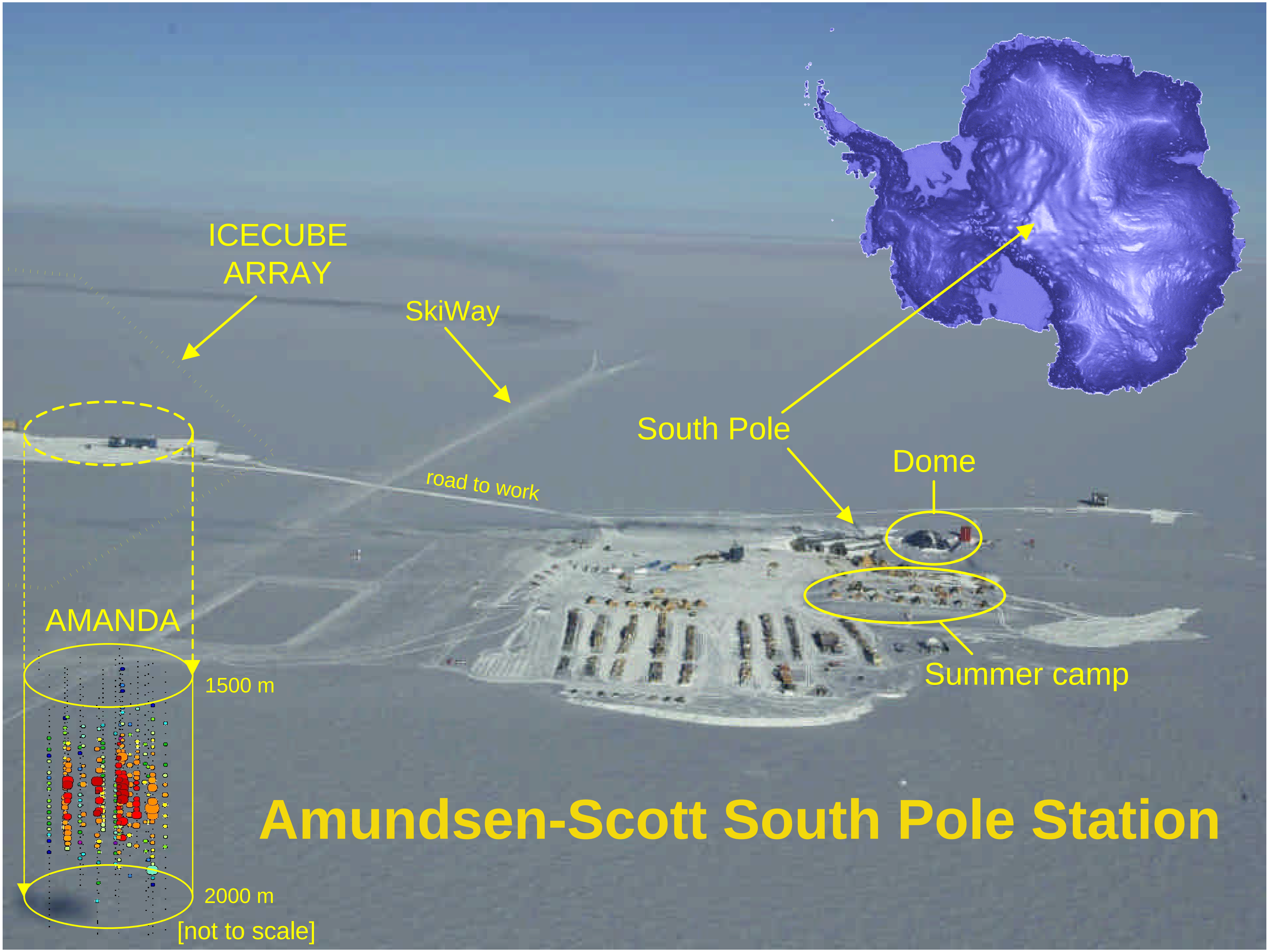
- > 5000 Detectors

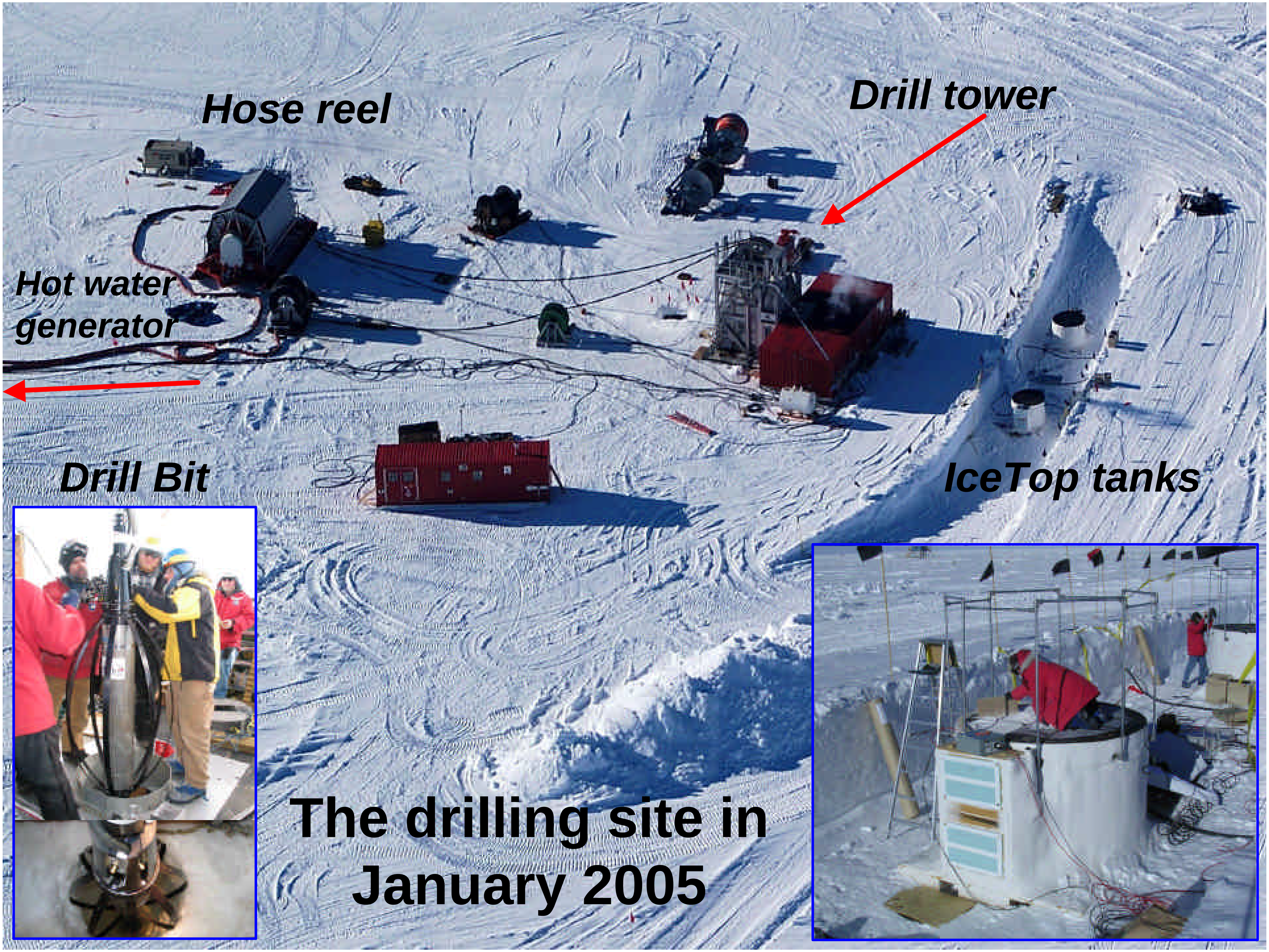


- > 240km of Cable



- ~ 1 Billion tons of ice


ICECUBE
ARRAY
SkiWay
road to work
South Pole
Dome
Summer camp
AMANDA
1500 m
2000 m
[not to scale]
Amundsen-Scott South Pole Station



The drilling site in January 2005

Physics Driven Requirements

- Timing Accuracy: 5ns RMS → 2ns RMS
- Charge Dynamic Range:

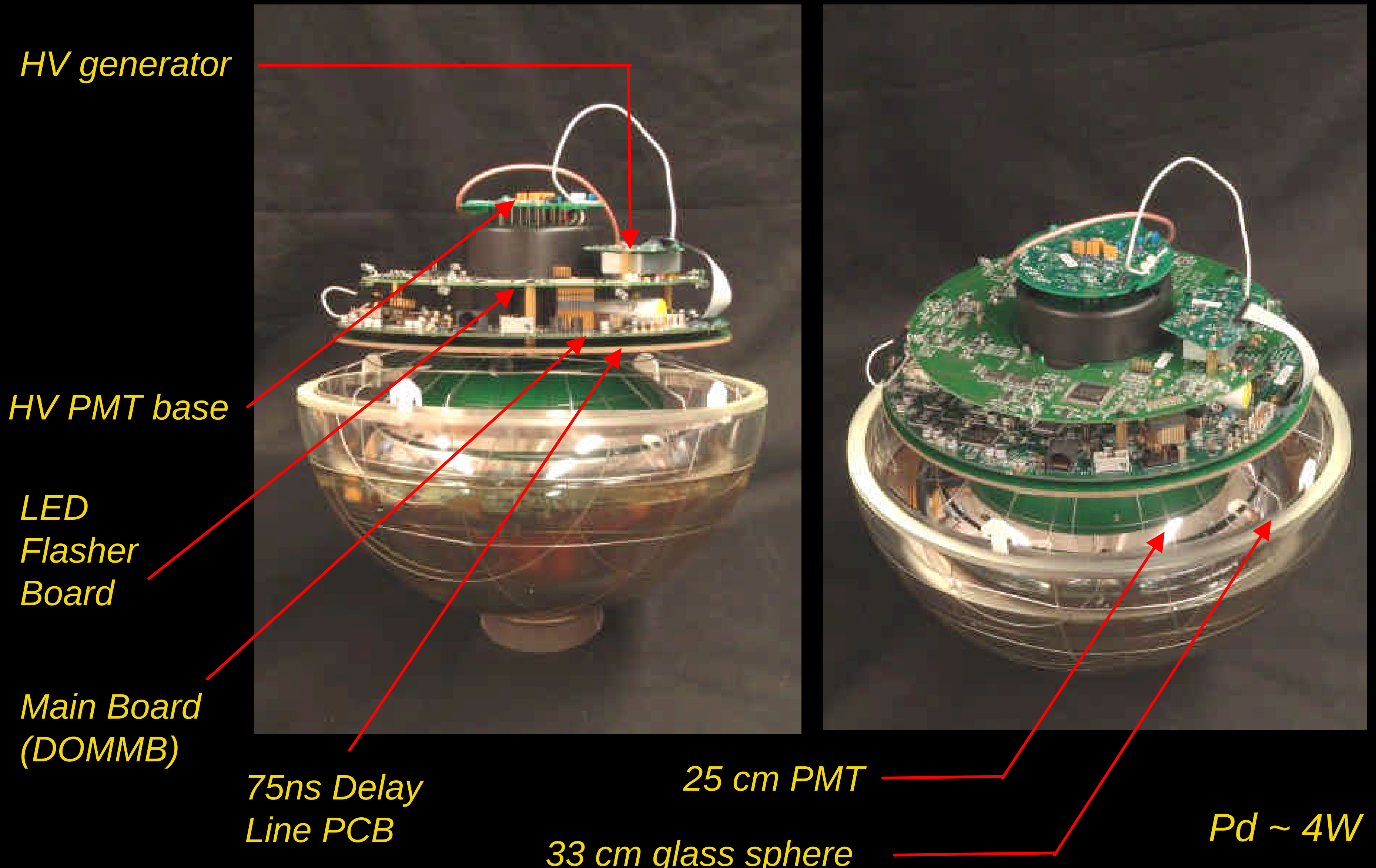
  >200PE/15ns → ~500PE/15ns
- Waveform capture:

  300MS/s for 400ns, 40MS/s for 6.4µs
- In-Situ Calibration and Diagnostics
- In-Ice Hardware Local Coincidence

Design Requirements

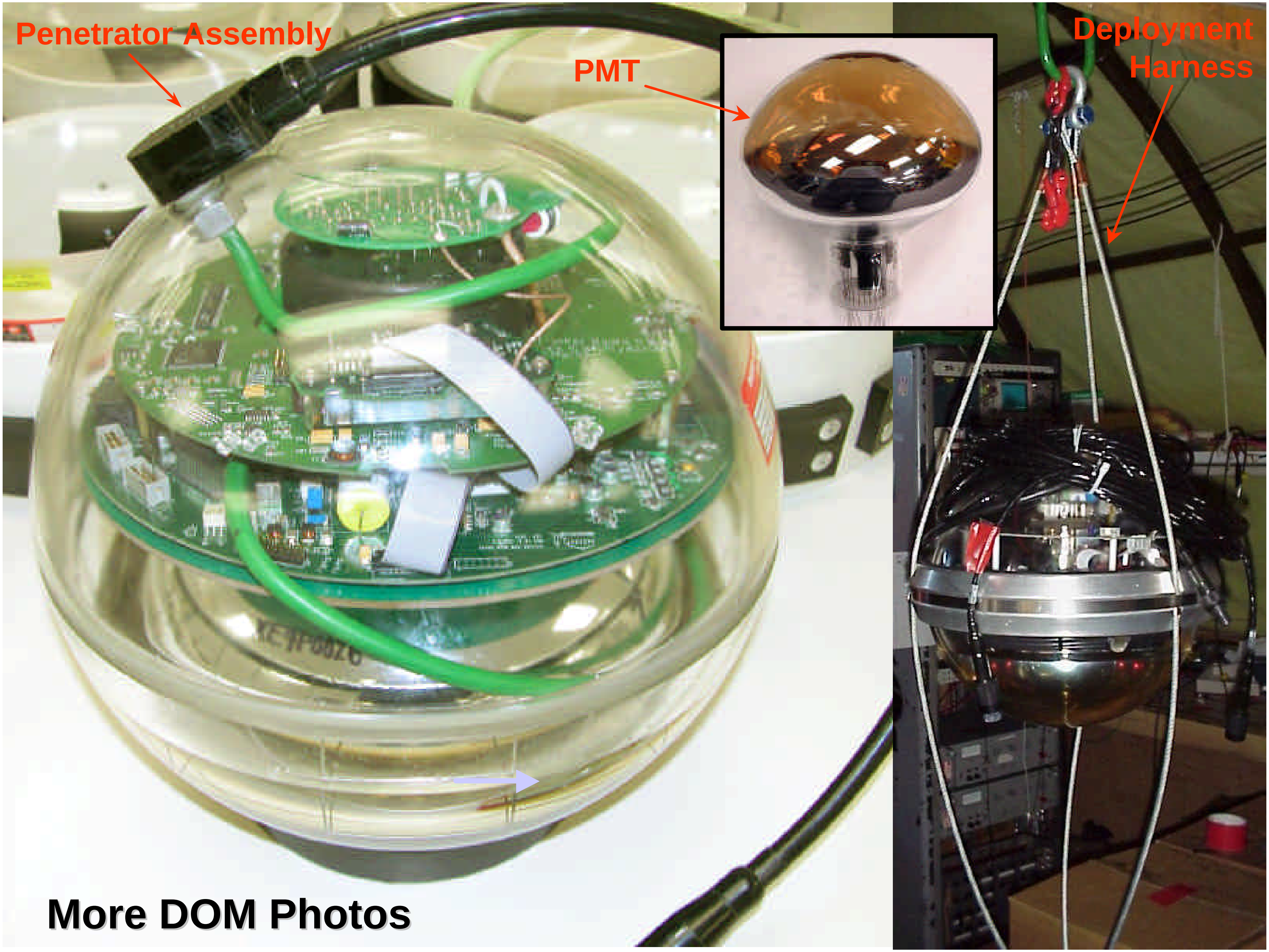
- Detector modules must operate for 10 years after installation is complete
- Multi-drop, single pair, communication and power
  - 2 detectors share 1 twisted pair (minimize cost)
  - Failure of 1 detector must not disable an entire string
- Remote operation
  - Access to DOMs from Northern Hemisphere minimizes manpower required at the South Pole
- Resistant to Radio Frequency Interference from other South Pole experiments (VLF, Radar)
- Expected Hit rate ~0.8 kHz
- Low power consumption < 5W/DOM
  - Minimize fuel consumption

Digital Optical Module (DOM)



Pd ~ 4W

More DOM Photos



IceCube’s First String: January 28, 2005

27.1, 10:08: Reached maximum depth of 2517 m

28.1, 7:00: preparations for string installation start

9:15: Started installation of the first DOM

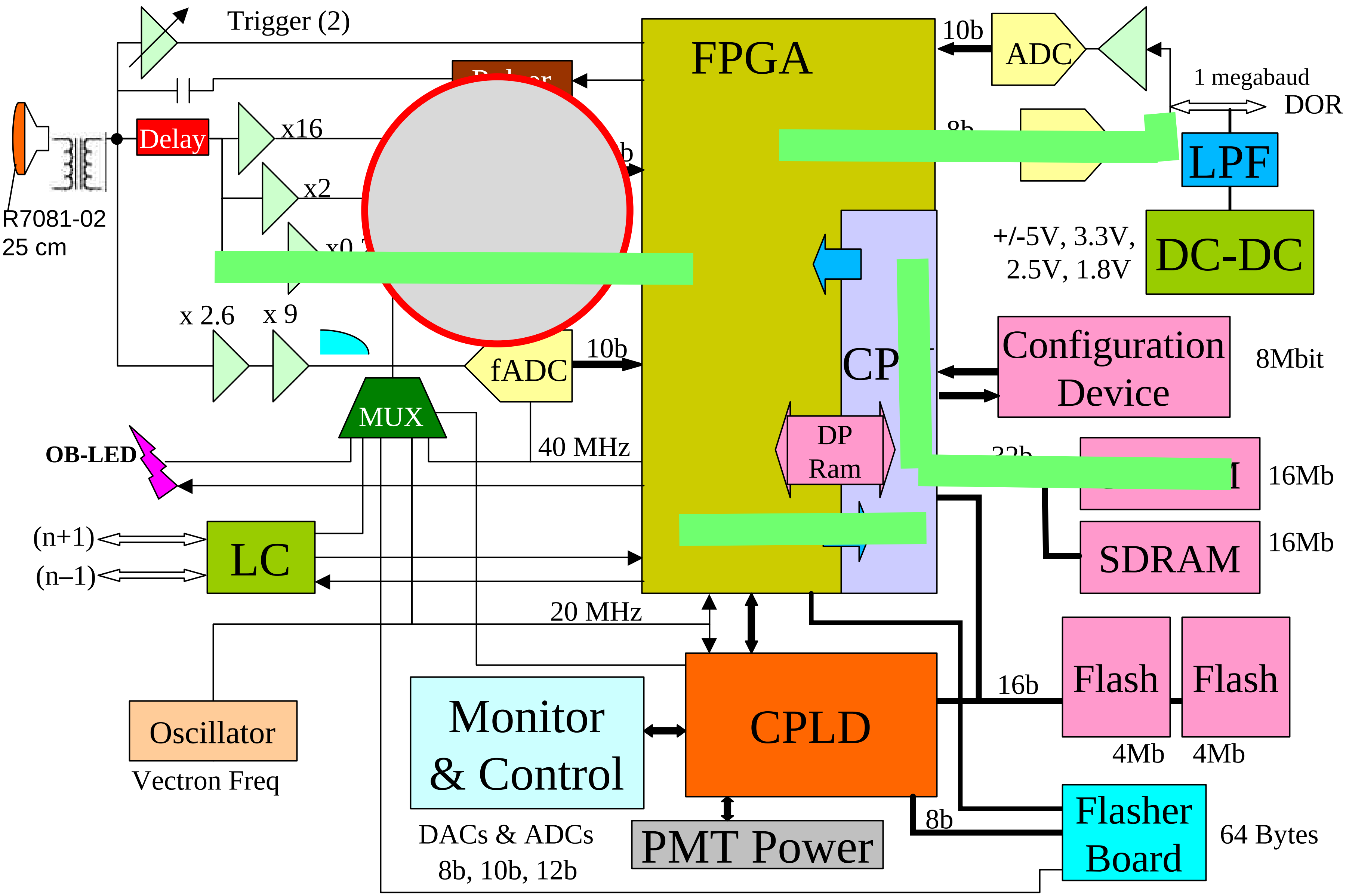
22:36: last DOM installed
12 min/DOM

22:48: Start drop

29.1, 1:31:
String secured at depth of **2450.80 m**

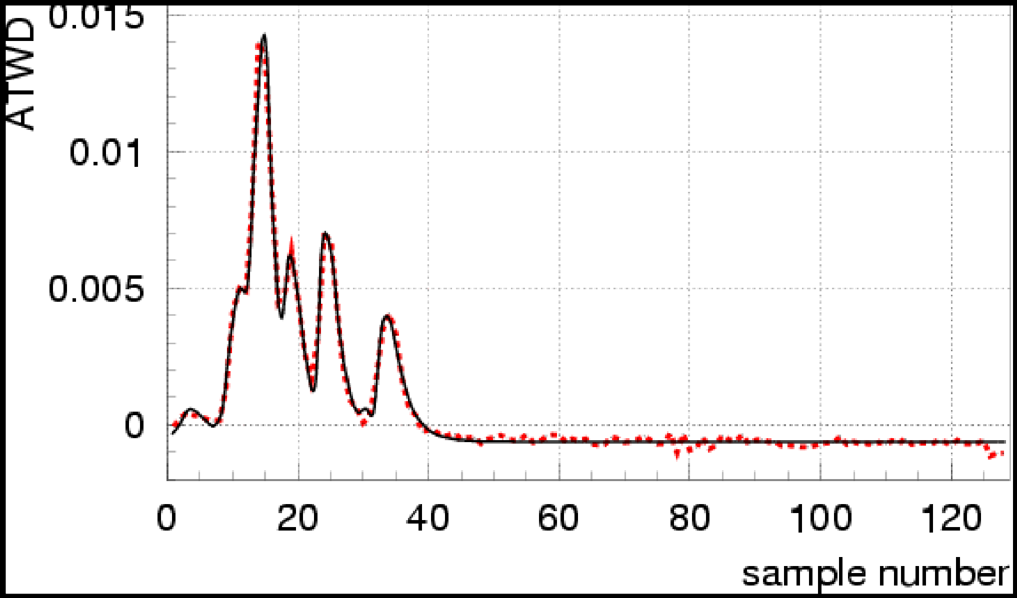
20:40: First communication to DOM

DOM MB Block diagram



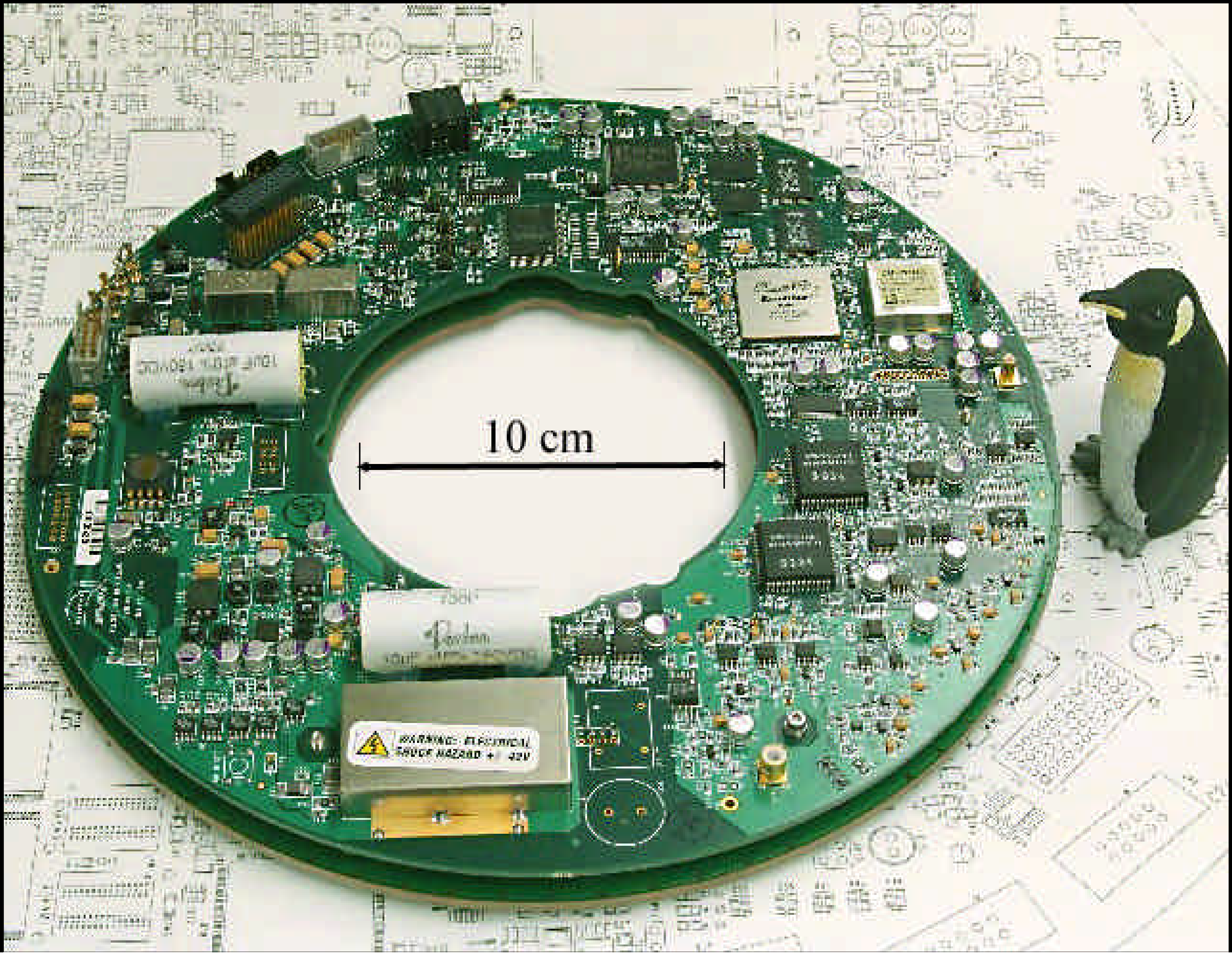
Analog Transient Waveform Digitizer

- LBNL designed custom ASIC
- Variable sampling speed: 250 - 800 MHz
- Power consumption 125 mW
- Digitization: 10 bit, 30 ms /channel
- 4 channels x 128 samples deep, acquisition on launch
- Design: ~1996 (also used in KamLAND, NESTOR)



2 ATWD/DOM: 0.25 W

Digital Optical Module Main Board



So, you want to build a detector in the Polar Ice???

Pros of deploying in the Polar Ice

- Deployment from Terra Firma
- Well established infrastructure provided by South Pole Station

The list of pros is significant !!

- No radioactivity in ice ⇒ PMT rate < 1kHz **~600Hz**
- Very stable temperature environment once the DOMs are deployed and freeze back is complete
  - No water trying to leak into the glass sphere

Cons of deploying in the Polar Ice

- **Weather Conditions**
  - Can cause delays with arrival and departure of resources
  - Surface temperatures: Can get as low as -40^{o}C during the deployment season (-110^{o}C “off-season”)

Cons of deploying in the Polar Ice

- **Expensive**
  - Fuel is everything!!

Hot water drill ➔ 7000 gallons/hole

Cons of deploying at the South Pole

- Short deployment season
  - We can only build the experiment at the South Pole for ~ 4 months of each year, during the Austral Summer

Cons of deploying in Ice

- High stress during the freeze-back of the holes on the cables, connectors, and optical modules

The exact amount of stress and added pressure is currently unknown, but we have a few cases in the ice now indicating that cables may have failed due to the stresses of freeze back

Investigations are planned for future deployments

Cons of deploying in Ice

- Once deployed, the detector modules are inaccessible to everything except the host communication system
  - – Must be built to last

Hi-Rel design methodology required

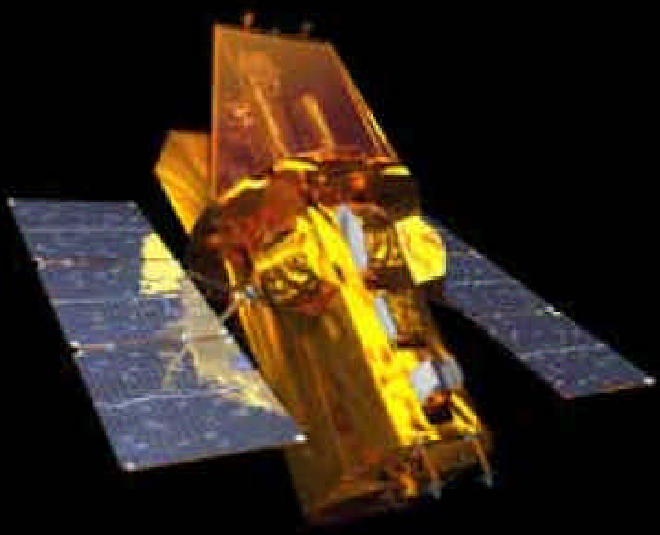
We need to identify all defective boards before they are deployed in the ice

The list of cons is significant !!

High-Rel Design Challenges

Design for Space application …

on a consumer electronics budget



High-Rel Design Challenges

- 10 years of operation after construction
- <0.2%/yr catastrophic failure allowed
- <1%/yr partial failure allowed
- No hardware maintenance after deployment
- Minimal MTBF data for low temperature applications
- Cost vs component quality and performance
  - Commercial → Industrial → MIL-STD

High-Rel Design: Firmware

- Robust Boot Mode
  - **Simple** boot image in memory to allow successful communications with the host at power-on
  - Additional functions:
    - Flash memory programming
    - Selective reboot from flash memory

High-Rel Design: Components

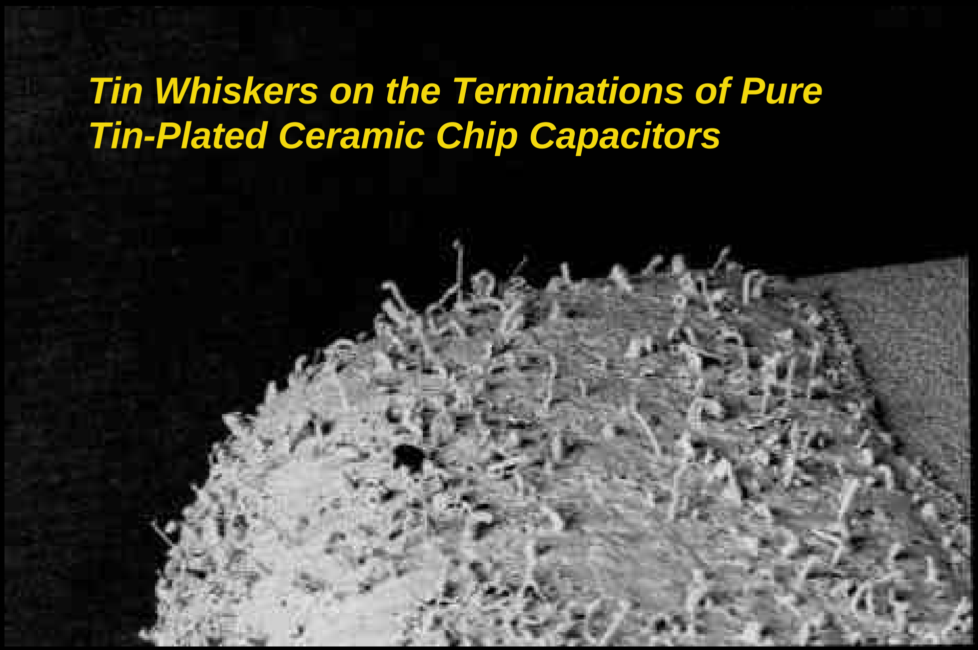
- All components and fabrication vendors must be on our Qualified Manufacturer List
  - Review of reliability history of component manufacturers
  - Site survey of all fabrication vendors
- GIDEP (Government-Industry Data Exchange Program)
  - Great resource
    - MIL-STD, RoHS (Pb free) compliance, and component reliability information

High-Rel Design: Components

- Component Selection
  - Select only High-Rel, MIL and/or Industrial grade components
  - Derate all components
    - Not much information for cold temperatures
  - No Al electrolytic capacitors allowed
    - The dielectric dries up over time
    - Hi-Rel, Oscon type used instead
  - Component performance variations at cold temperatures ➔ In-test part screening
  - Pure Tin plating avoided where possible

High-Rel Design: Components
(Lessons learned from others!)

- Pure Sn avoided wherever possible
  - Industry shift to RoHS compliance
  - List of failed NASA missions due to metal whisker growth is long and well-documented

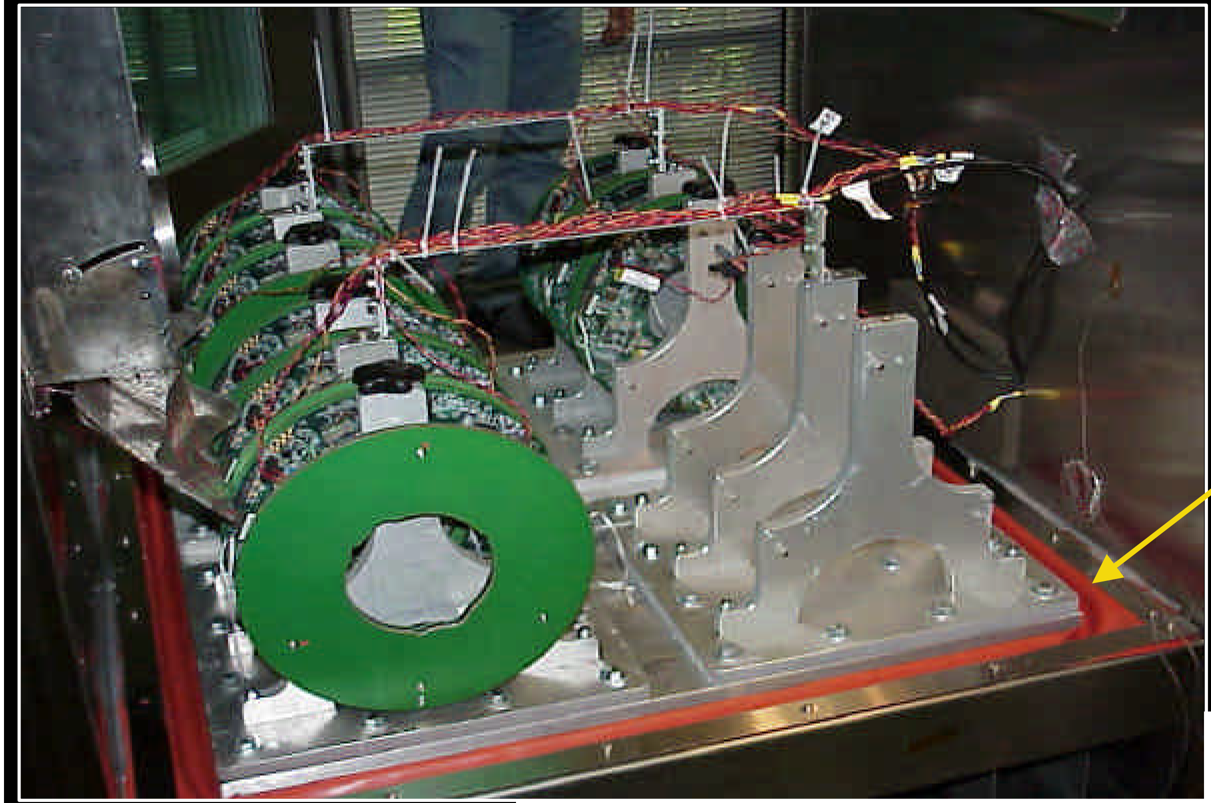


Images taken w/o permission from NASA/Goddard Website

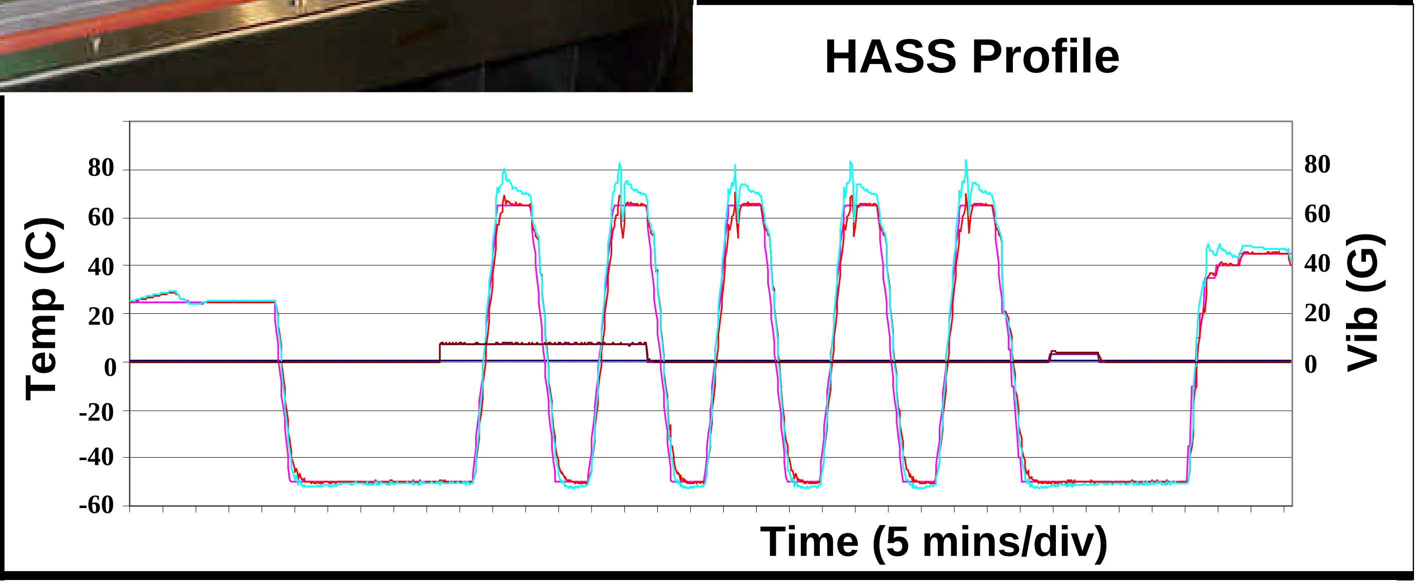
High-Rel Design: Testing

- HALT (Highly Accelerated Lifetime Testing)
  - +80ºC to –80ºC cycles with 30g of random vibe
  - One time procedure on multiple boards
  - This is your best attempt to try to break the finished board
  - Used to expose any part that may not operate in the required temperature range
- HASS (Highly Accelerated Stress Screening)
  - Standard part of the test procedure for the first 3 production years

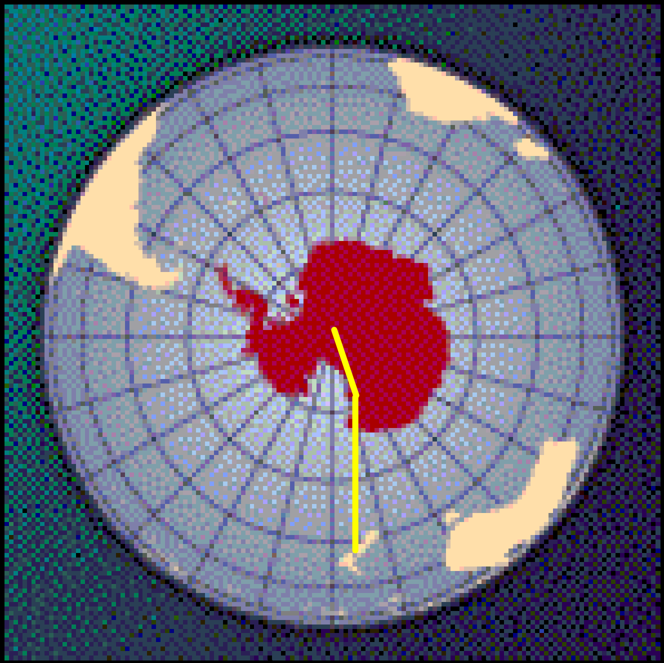
HALT and HASS Fixture and Profile



Shake Table -
In HASS Chamber



Why do we vibrate the boards????



1. Air freight from Berkeley to Wisconsin, Germany, and Sweden
2. Air freight from Wisconsin, Germany, and Sweden to Port Hueneme, CA
3. Container ship from Port Hueneme, CA to Christchurch, NZ
4. Cargo Plane from Christchurch, NZ to McMurdo Station, Antarctica
5. Cargo Plane from McMurdo Station to the South Pole Station

Because if we don't, someone else will !!!

High-Rel Design: Test Results
(Lessons learned on our own)

- In the pre-production years, we found and replaced components that did not operate properly at low temperature
  - Early in design stage → Possible to replace suspect parts with similar parts from other manufacturers

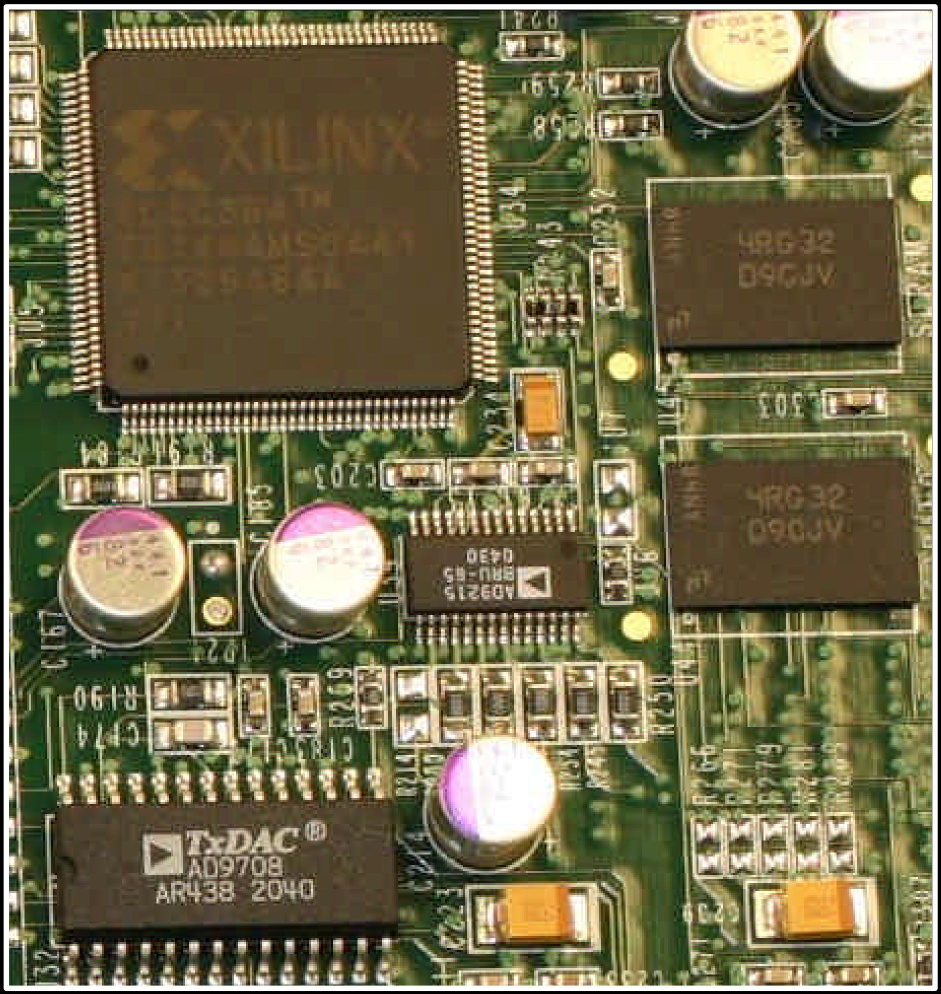
- During the first 2 years of production we faced 2 component issues that were temperature dependent
  - Mature design → We were able to modify SW and FW to solve both issues

Production Guidelines

- IPC610 class 3 workmanship and inspection for PCB fabrication and loading
  - Medical and Satellite standard process
- Strict rework limits
  - No unplanned jumper wires on deployable boards
  - Part replacement limits
- ESD Precautions mandatory

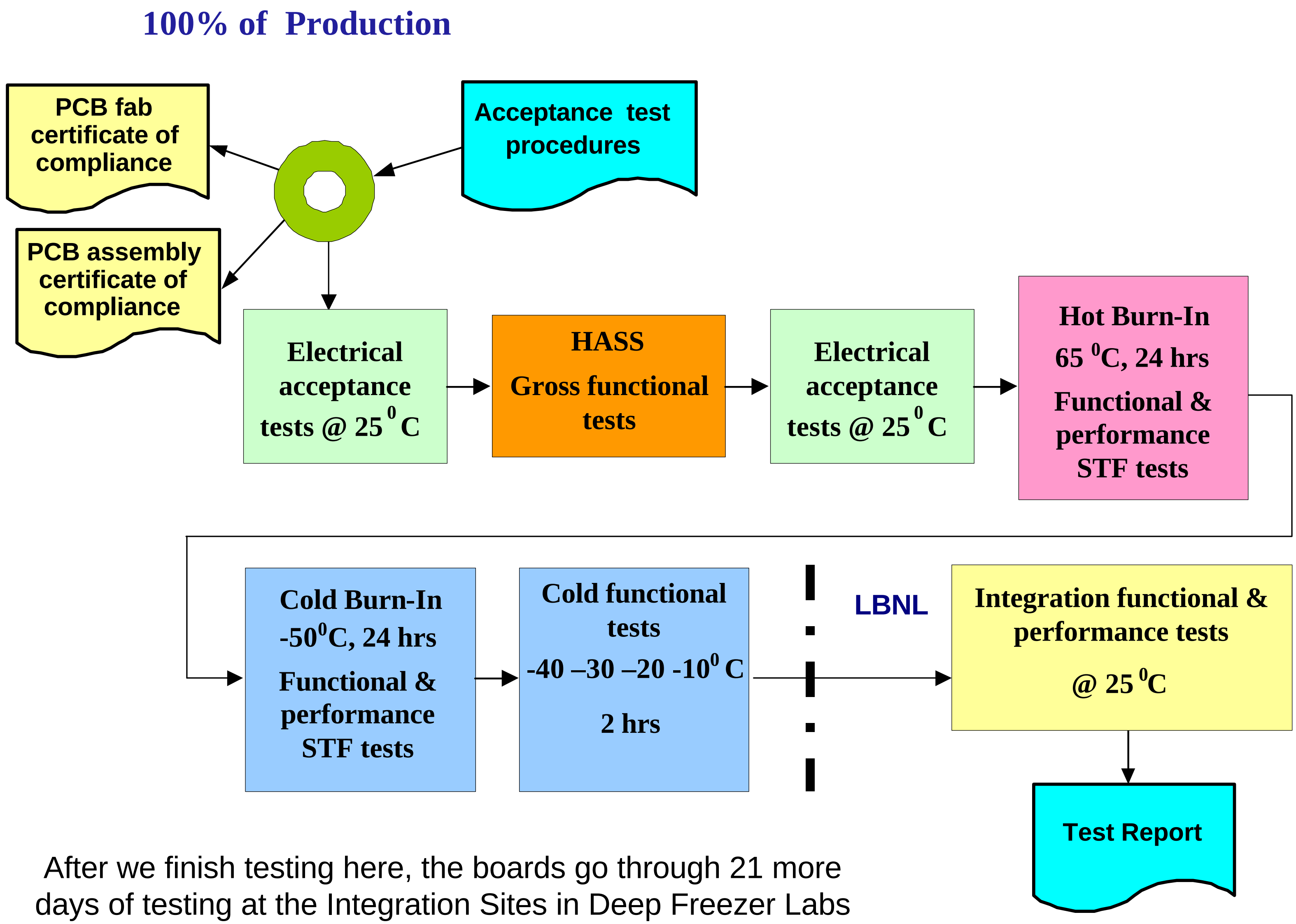
Part Tracking

Digital picture of Main Boards after loading used to track date codes on components



Production differed from other projects, because we don't routinely build thousands of units

Test Flow ➔ Test…Test…Test



Flow of production DOMMBs through acceptance testing

Burn-In and Interface Test Stands

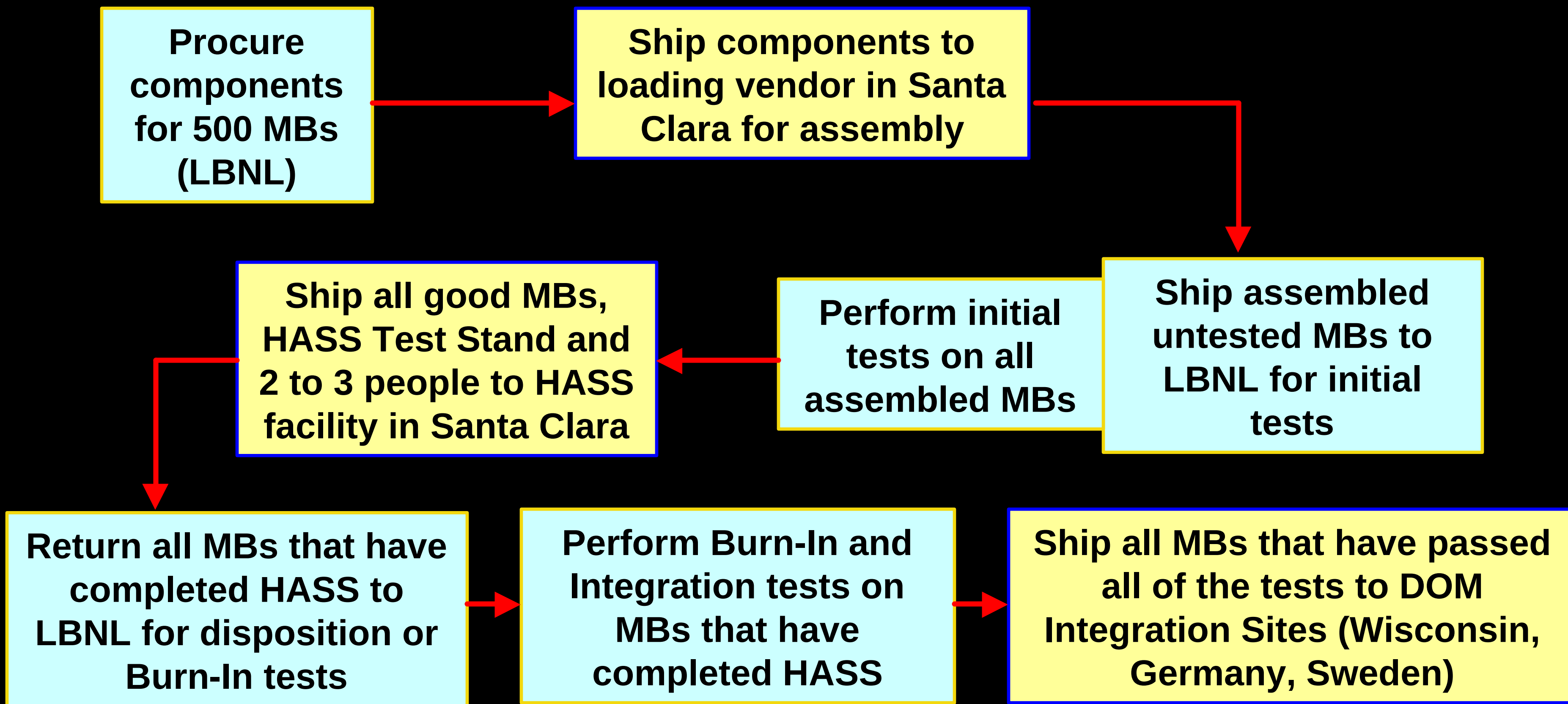
Each Main Board must pass all tests multiple times and is powered on for a minimum of 21 days at operating temperature

Large environmental chamber allows simultaneous Burn-In of 64 MBs

Old Integration box shown, new version allows simultaneous Integration testing 8 MBs

~2000 DOM Main Boards produced and tested at LBNL from 6/04 to 3/06

Production Plan – Year 1



- This process model is very complicated and expensive
- Increase in device handling and movement influenced yield

Production Year 1

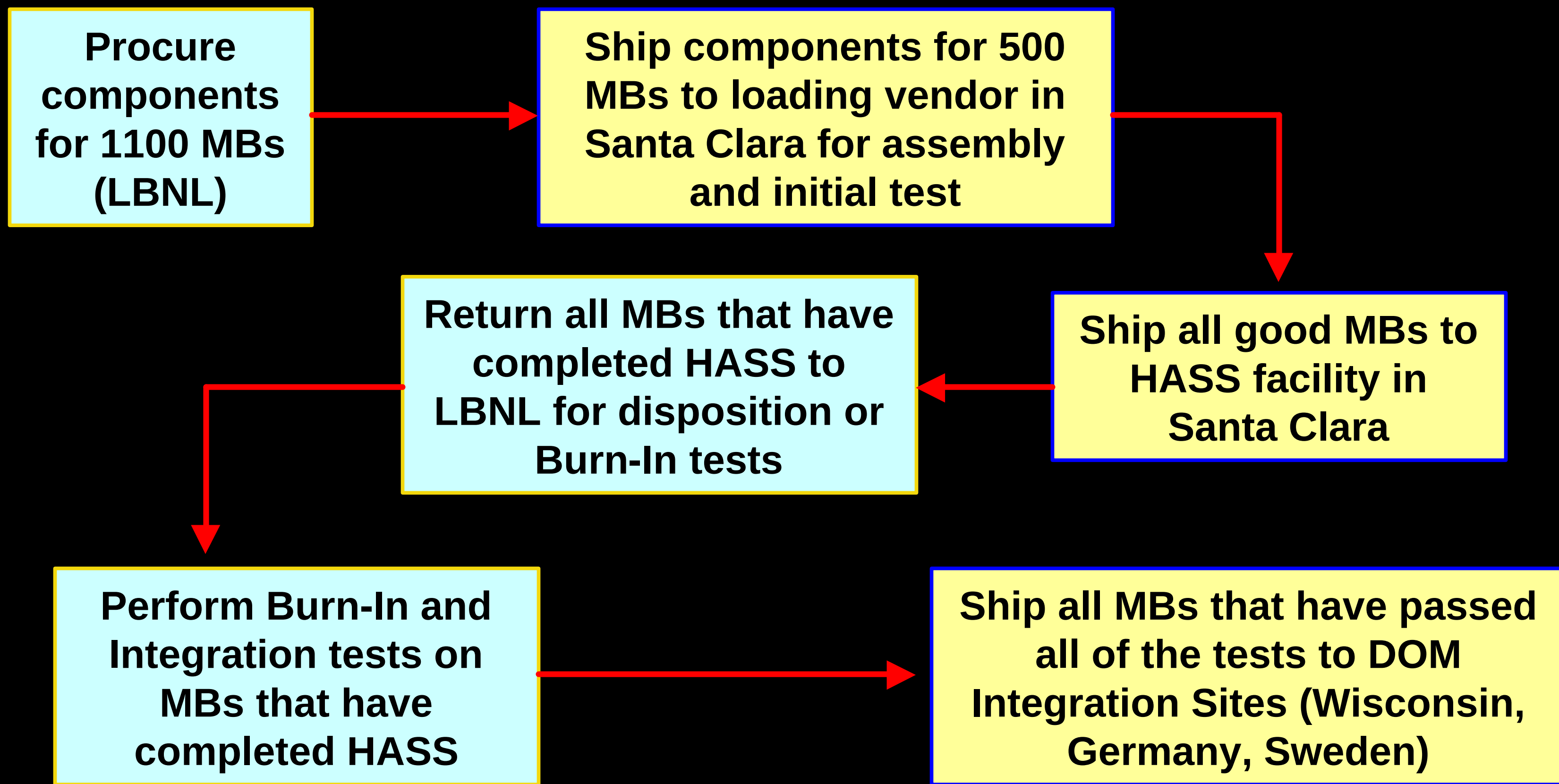
Expectation

- Deliver 400 working DOM main boards to Worldwide Integration Sites
- Plan: Build 500 using smaller fabrication and assembly vendors, expect a first pass yield of 80%, and do **NO** rework on any board

Reality

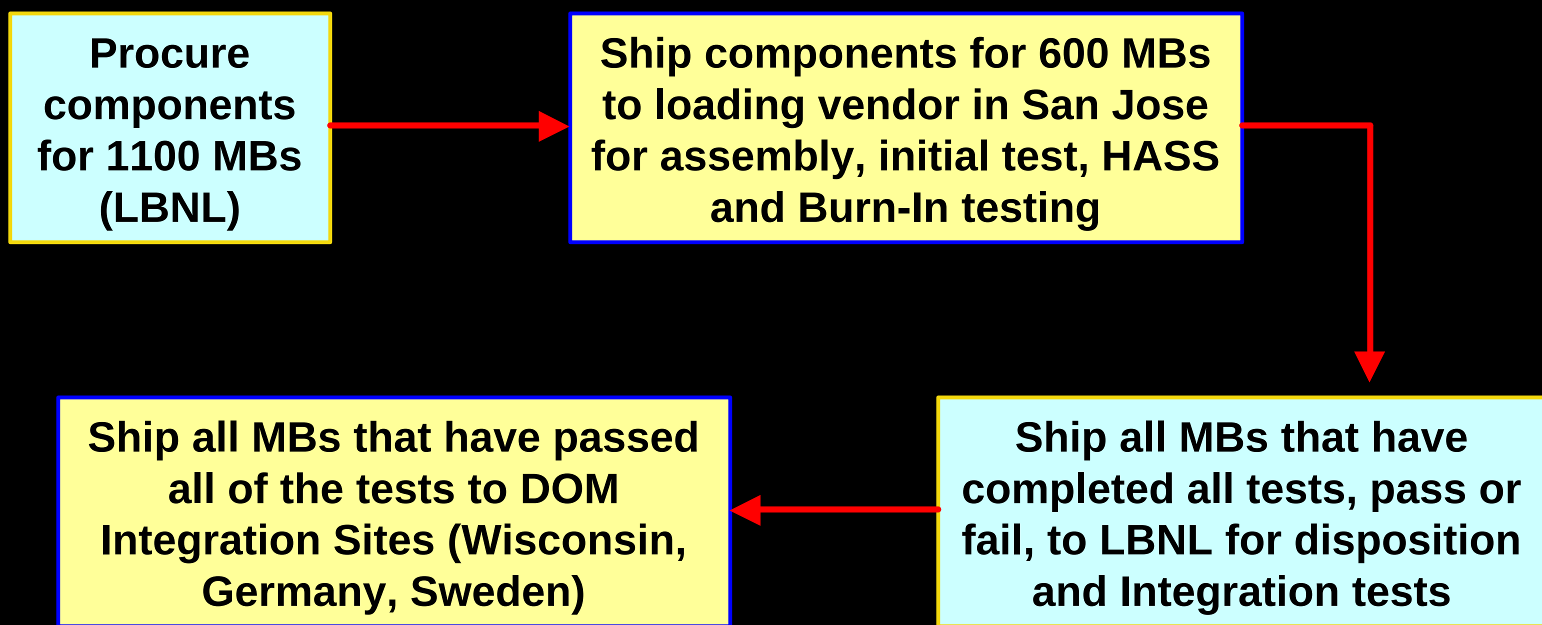
- First pass yield was ~ 60%, so we reworked ~100 boards to meet our delivery goal
- As a result, we were late delivering boards to the Integration Sites, we were extremely over-worked due to the firm deadlines of the South Pole deployment season, and we caused schedule and resource problems at other institutions

Production Plan A – Year 2



- Only small changes from year 1 plan
- Inexperienced staff at HASS facility resulted in an increase in MBs that were diagnosed with false failures

Production Plan B – Year 2



- This process model is less expensive and less complicated than Flow A
- Experienced testing staff at fabrication vendor produced more reliable results

Production Year 2

Expectation

- Deliver 930 working DOM main boards to Worldwide Integration Sites
- Plan: Build 1100 MBs using a mix of small and medium size fabrication and assembly vendors, and make preparations to work through all yield issues

Reality

- First pass yield improved to about 70%
- There is still room to improve
- When the second part of the production cycle started, we were again behind schedule
- Because of the consolidation of assembly and full testing at the second fabrication house, deliveries were accelerated and we finished the season delivering all boards early

Production – Year 3

- Deliver 1300 working DOM main boards to Worldwide Integration Sites

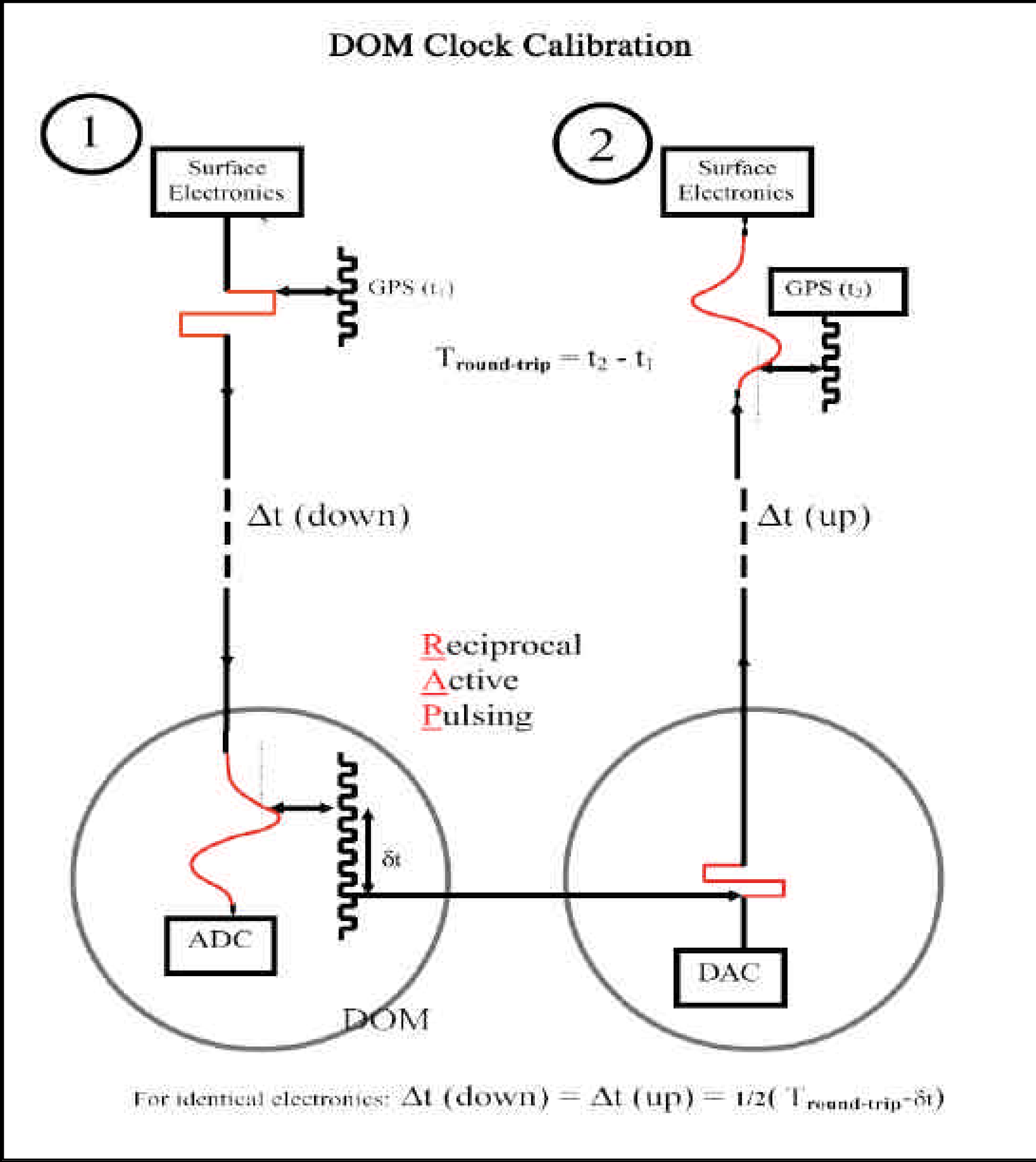
Turn-key contract for 1300 MBs to loading vendor in San Jose for assembly, initial test, HASS and Burn-In testing

Ship all MBs that have completed all tests, pass or fail, to LBNL for disposition and Integration tests

Ship all MBs that have passed all of the tests to DOM Integration Sites (Wisconsin, Germany, Sweden)

- This process model is less expensive and less complicated than all of the previous models
- First pass yield now greater than **85%**

Performance: **R**eciprocal **A**ctive **P**ulsing



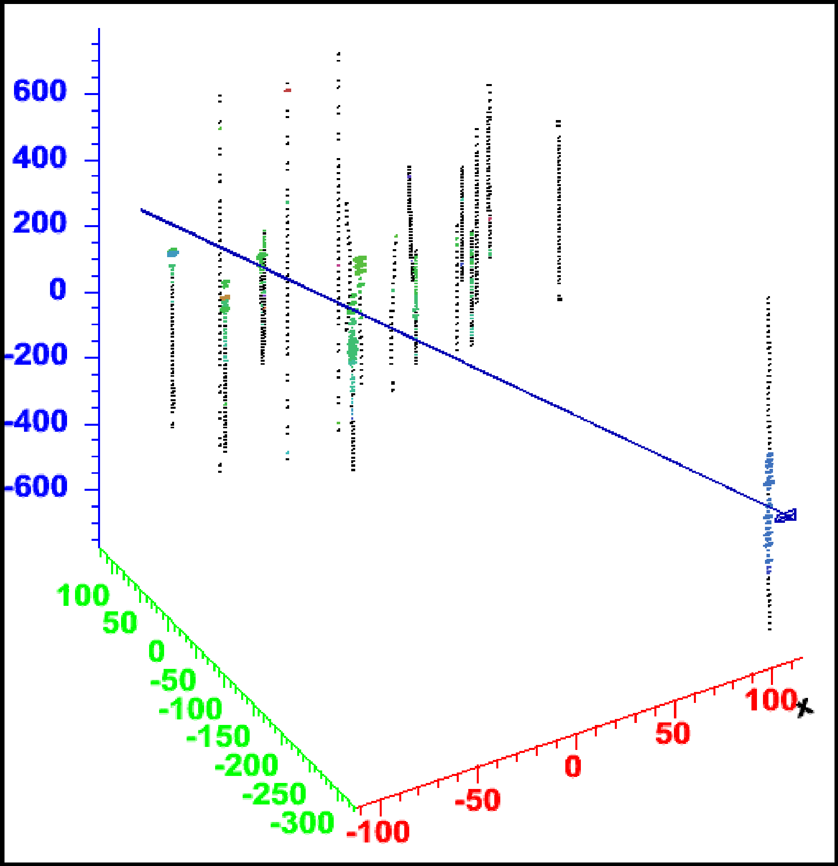
Relates the local free running DOM oscillators to the Universal Time Code standard transmitted by GPS satellites

Makes the 5000 DOMs in the detector and AMANDA look like they are running from a single common clock

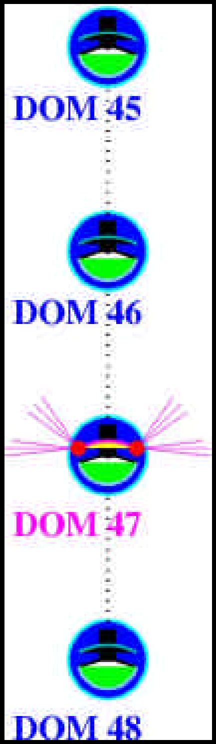
Reciprocal **A**ctive **P**ulsing Time Calibration

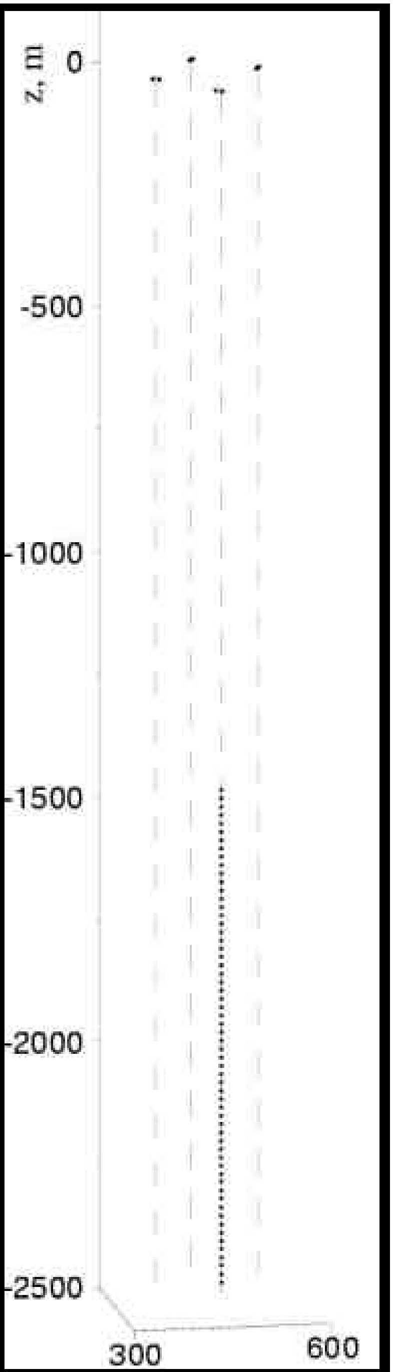
Verified with 3 sources: < ~1.7ns RMS

AMANDA ➔ IceCube coincidences



In-Ice Flasher boards

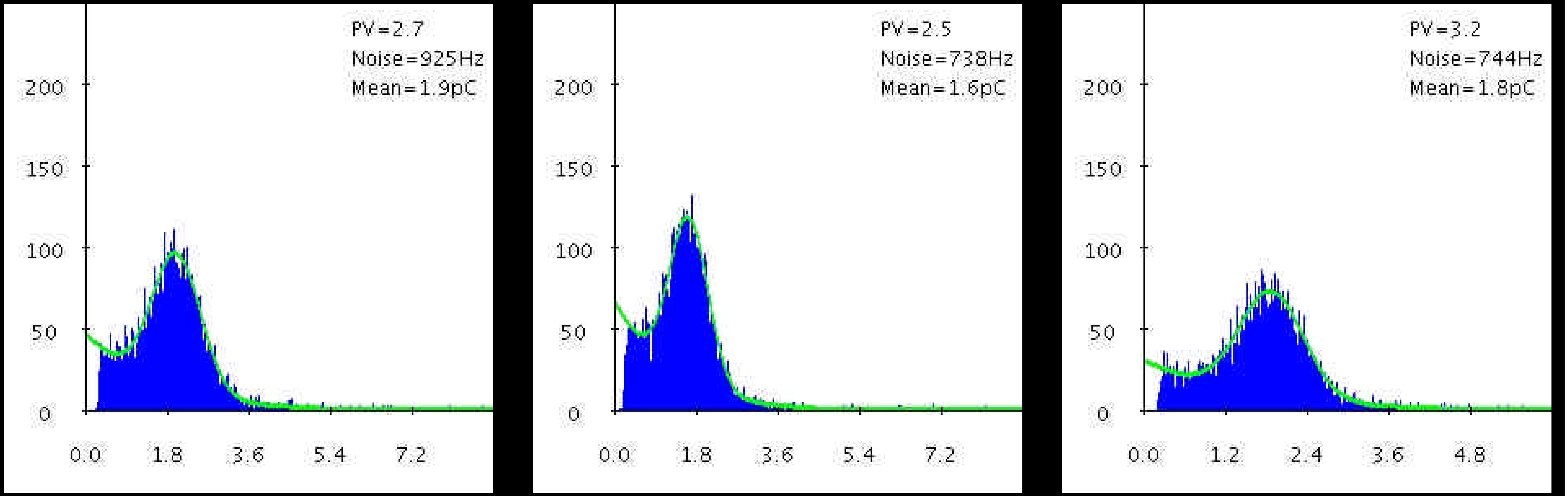




IceTop ➔ IceCube coincidences

Performance: Noise/Discriminator Threshold

- PMT Gain 10^7
- Noise in the ice for this data set was ~800Hz
- Discriminator Threshold as low as **~1/8** of a Single Photoelectron before triggering on electronic noise



Summary

- As of today, we have deployed 600 Detector Modules in the ice at the South Pole
  - 60 have been in operation for a full year – No Failures
  - 535 have been in operation since February – No Failures
  - 5 are currently off-line
    - Cable issues, high voltage failure, main board investigation
- We don’t know what will happen over the next 15 years that IceCube is in operation, but we feel confident that we have designed a product that meets or exceeds the system requirements for reliability and performance

Thank You


GEOGRAPHIC
SOUTH
POLE
ROALD AMUNDSEN
DECEMBER 14, 1911
"So we arrived and were able to plant our flag at the geographical South Pole."
ROBERT F. SCOTT
JANUARY 17, 1912
"The Pole. Yes, but under very different circumstances from those expected."
ELEVATION 9,301 FT.