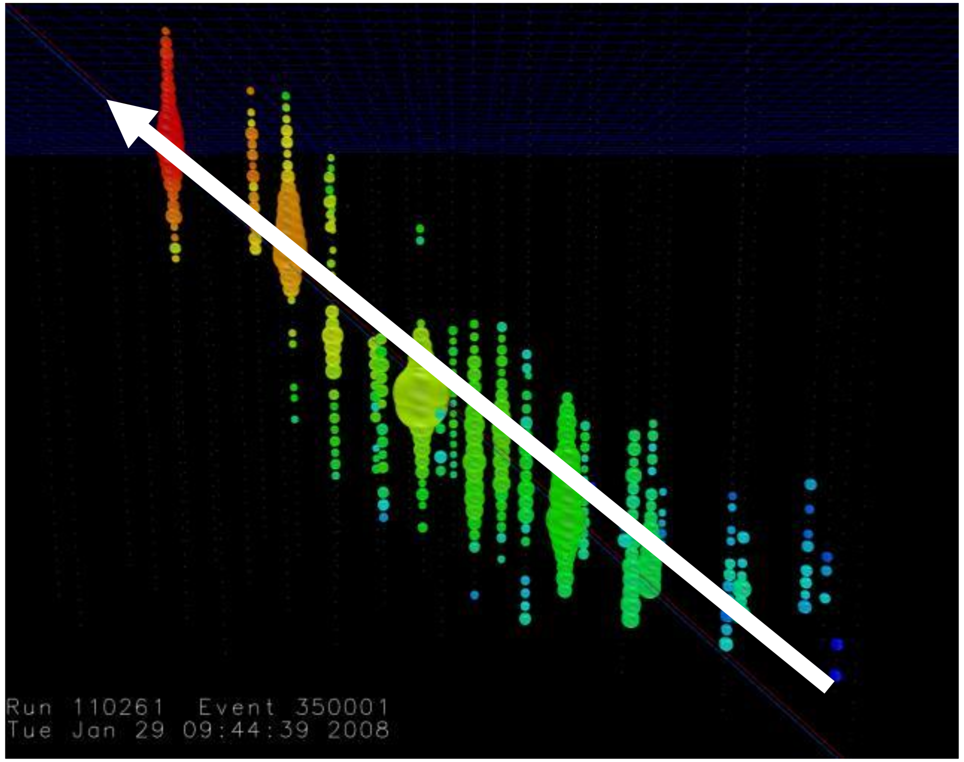
The Invisible Matters

How Program Management and Systems Engineering Teamed to Build the World's Largest IceCube

Randall C. Iliff



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Please Note

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Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

So, What’s an IceCube?

- “IceCube” is a cubic kilometer, gigaton scale Discovery Class research instrument now operating at the South Pole.
- IceCube is a unique telescope, able to look in all directions at once.
- Instead of light, this telescope captures ghostly, virtually undetectable subatomic particles known as neutrinos.
- IceCube has been fully operational for ten years.

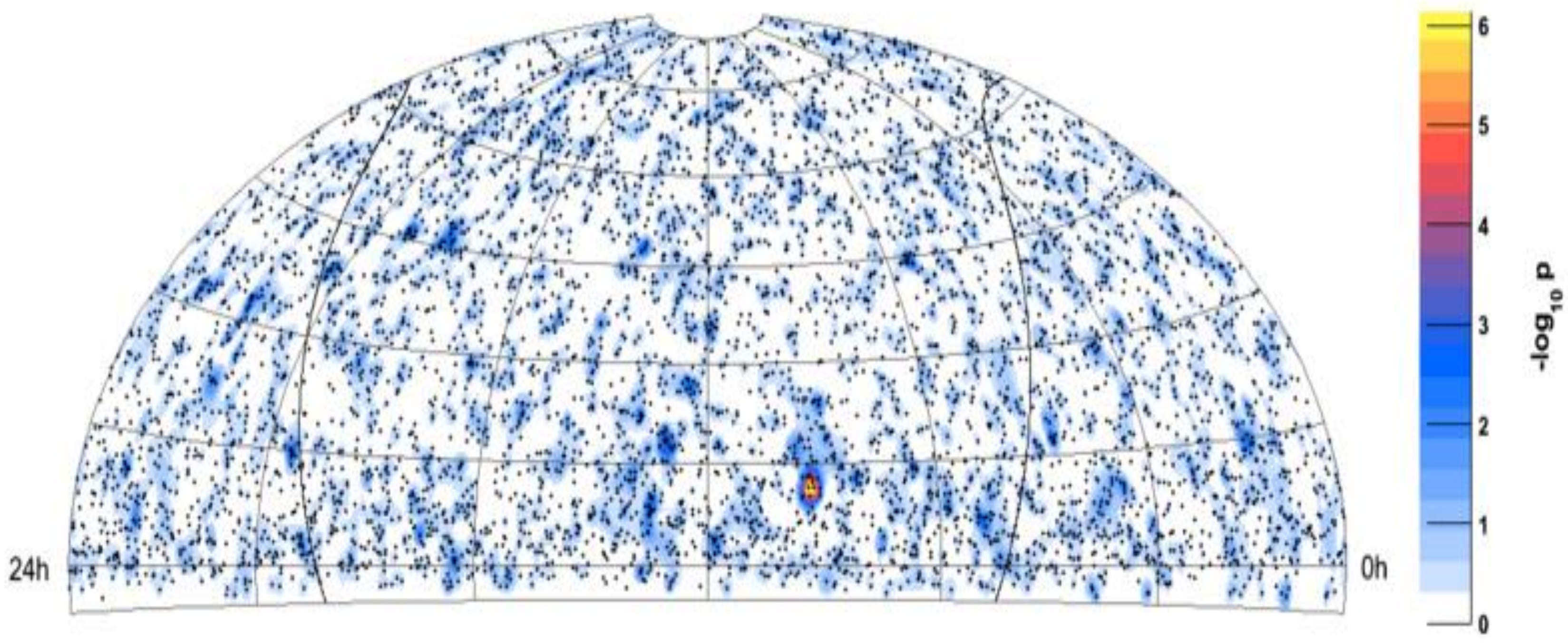
So, What’s a Neutrino?

- Neutrinos are the 2nd most common particle in the universe.
- Invisible, nearly massless subatomic particles.
- They travel at nearly the speed of light.
- They travel in straight lines from their source.
- They are not deflected by magnetic fields or absorbed by matter.

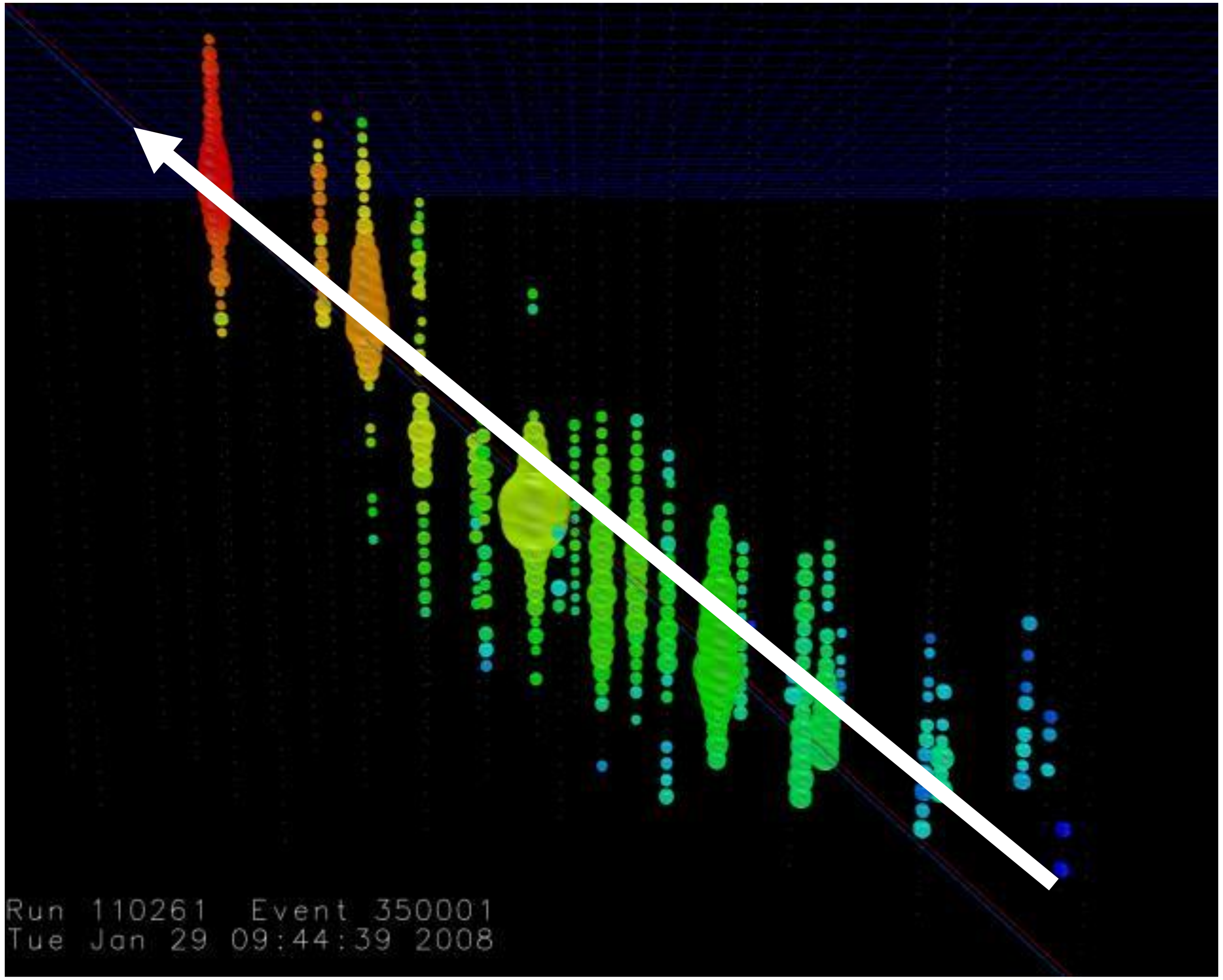
- Neutrinos make great messengers- IF you can detect them.

Where do Neutrinos Come From?

Depending on type and energy, anywhere from cosmic ray interaction in our own atmosphere to extra-galactic sources!



What Does an Event Look Like?



IceCube for Physicists and Engineers

Physicists:

- The world’s most powerful neutrino telescope.
- Nearly unlimited potential for discovery.
- A possible Nobel Prize.

Engineers:

- A massively complex story problem to solve.
- Challenging environment, little or no prior art.
- Anonymity if it works / blame if it doesn’t.

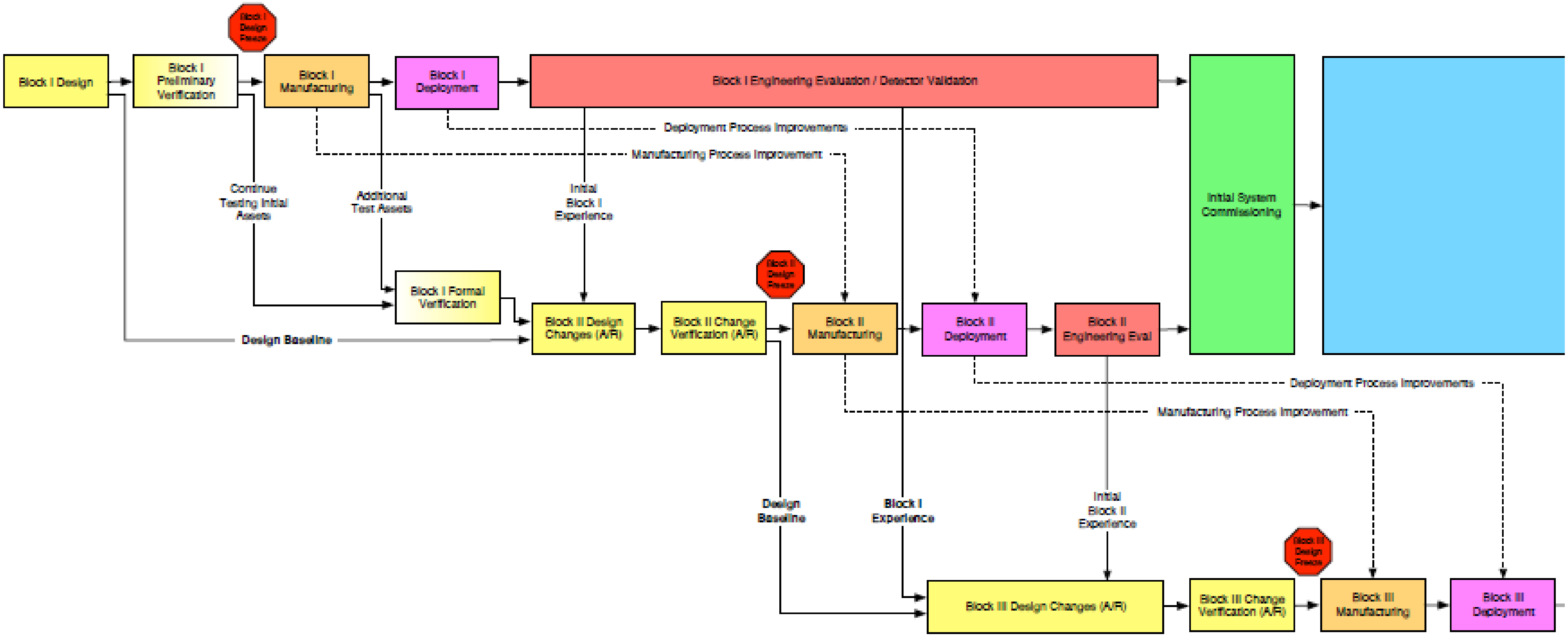
Two Fundamental Challenges

- The Technical Dimension:
  - Operational and support requirements.
  - Extreme environmental conditions.
  - Need for spacecraft level reliability.

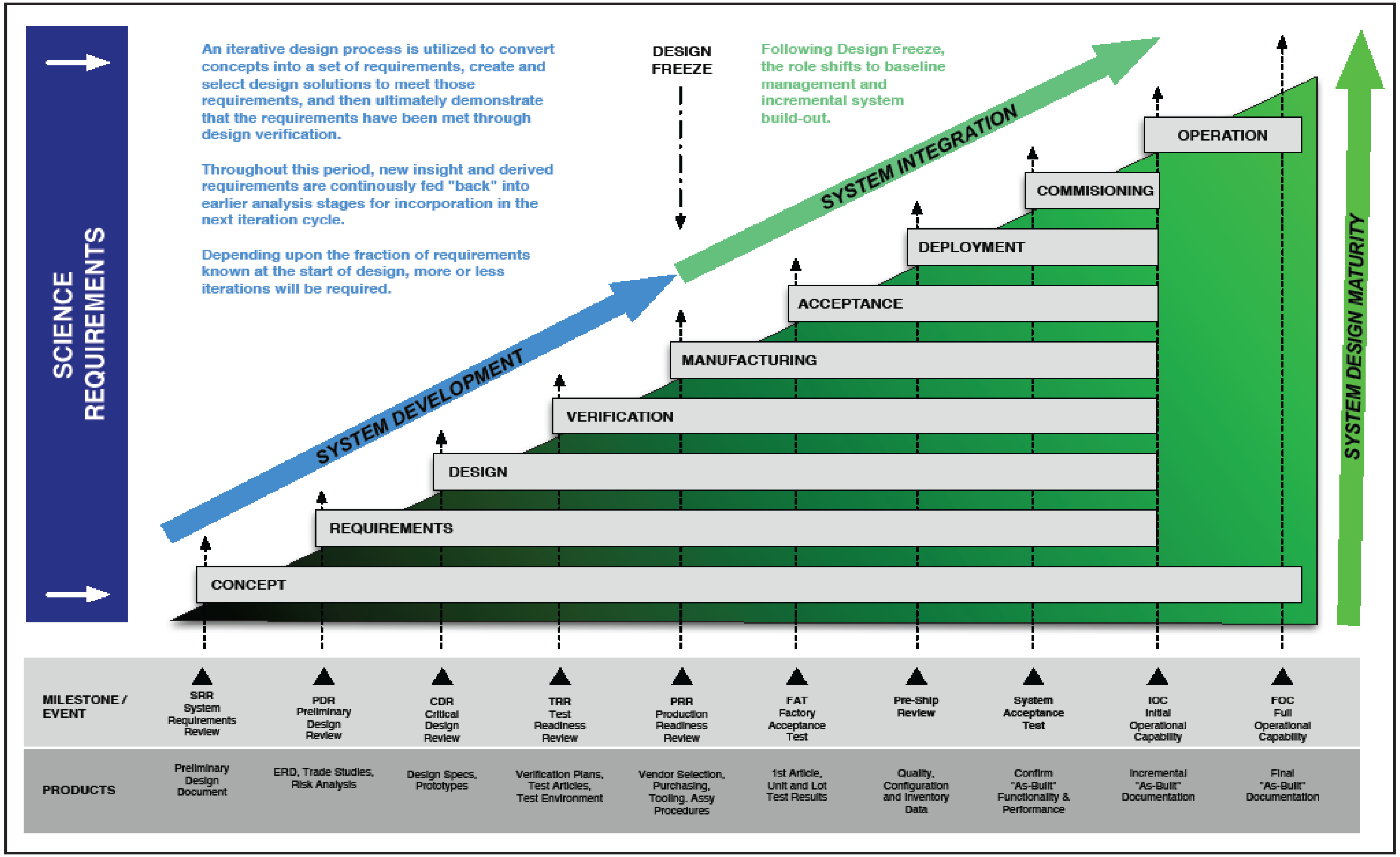
- Tailoring SE to Function in an Academic Setting:
  - Role was externally imposed upon the project.
  - Very limited SE awareness or buy-in.
  - Prior work patterns and relationships remained dominant.

Plus Working at the South Pole…

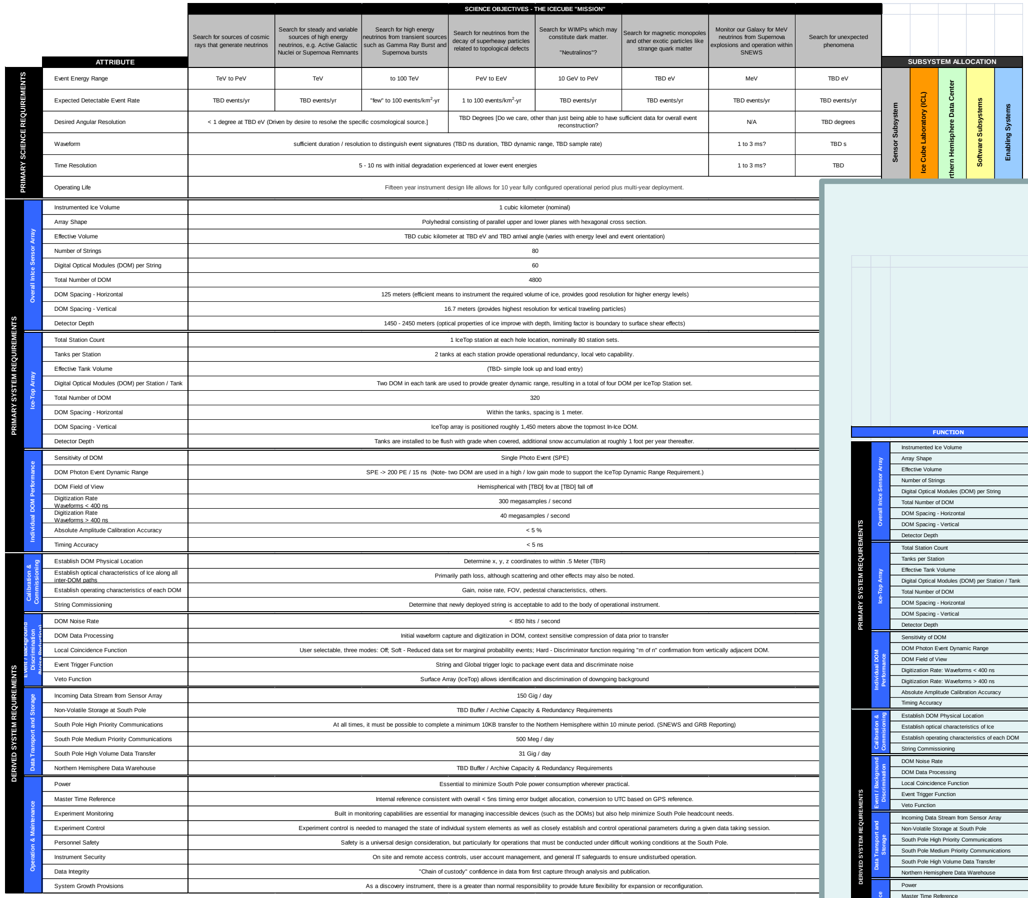
Development Leapfrog Required

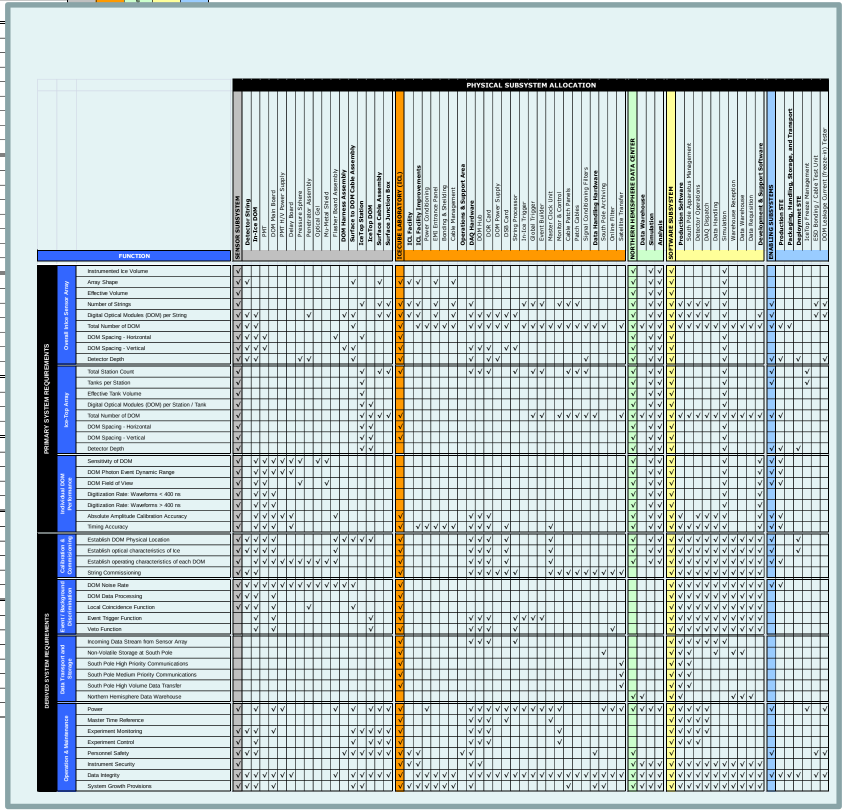


Simplified Systems Engineering Process

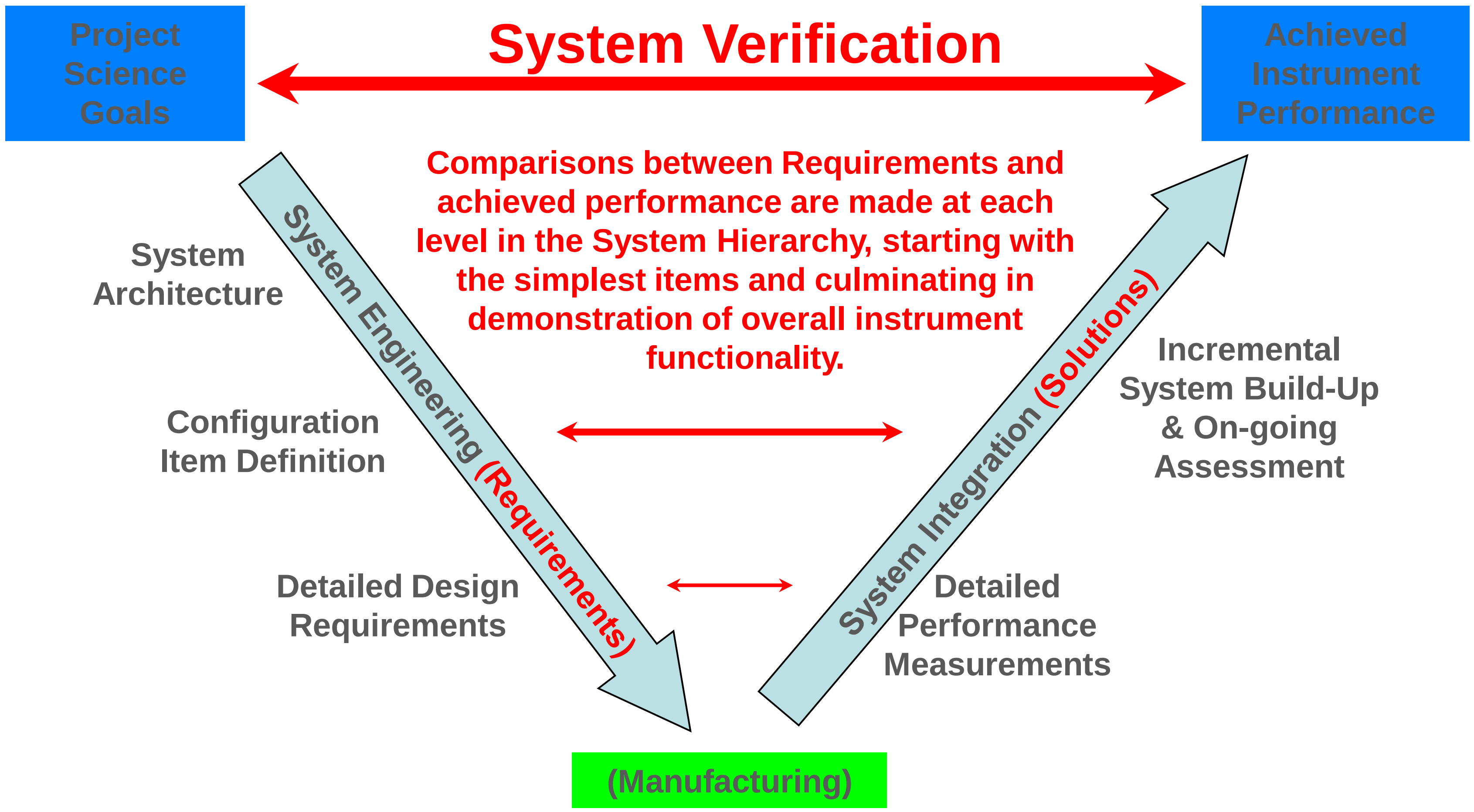


Overall Requirements Determined and Allocated to CIs

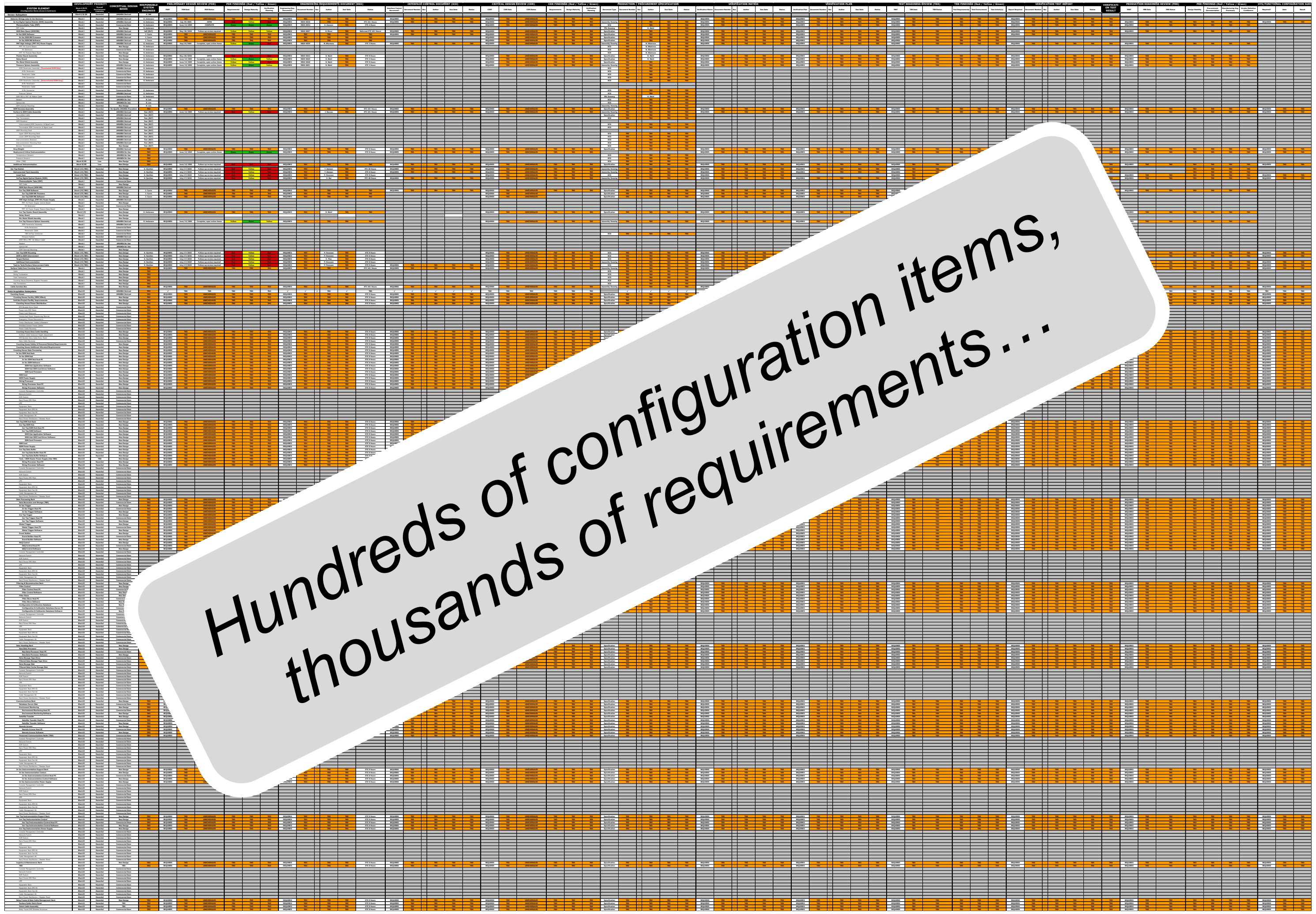




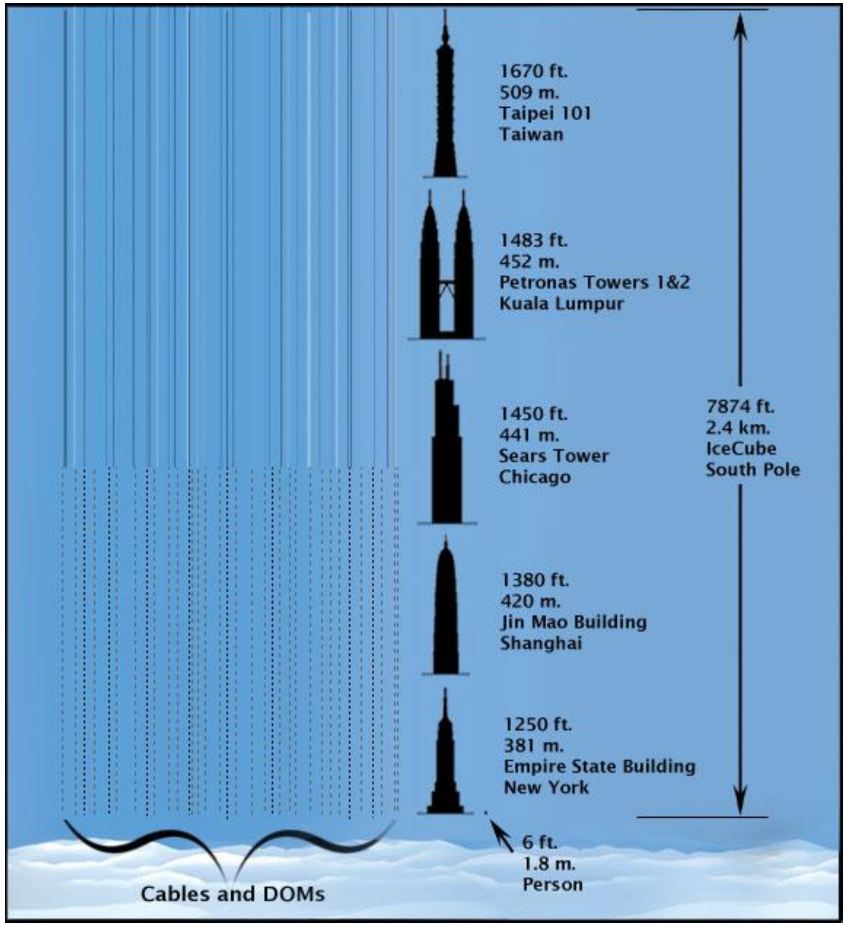
Emphasis on System Verification



Results in a Lot of Stuff to Track!

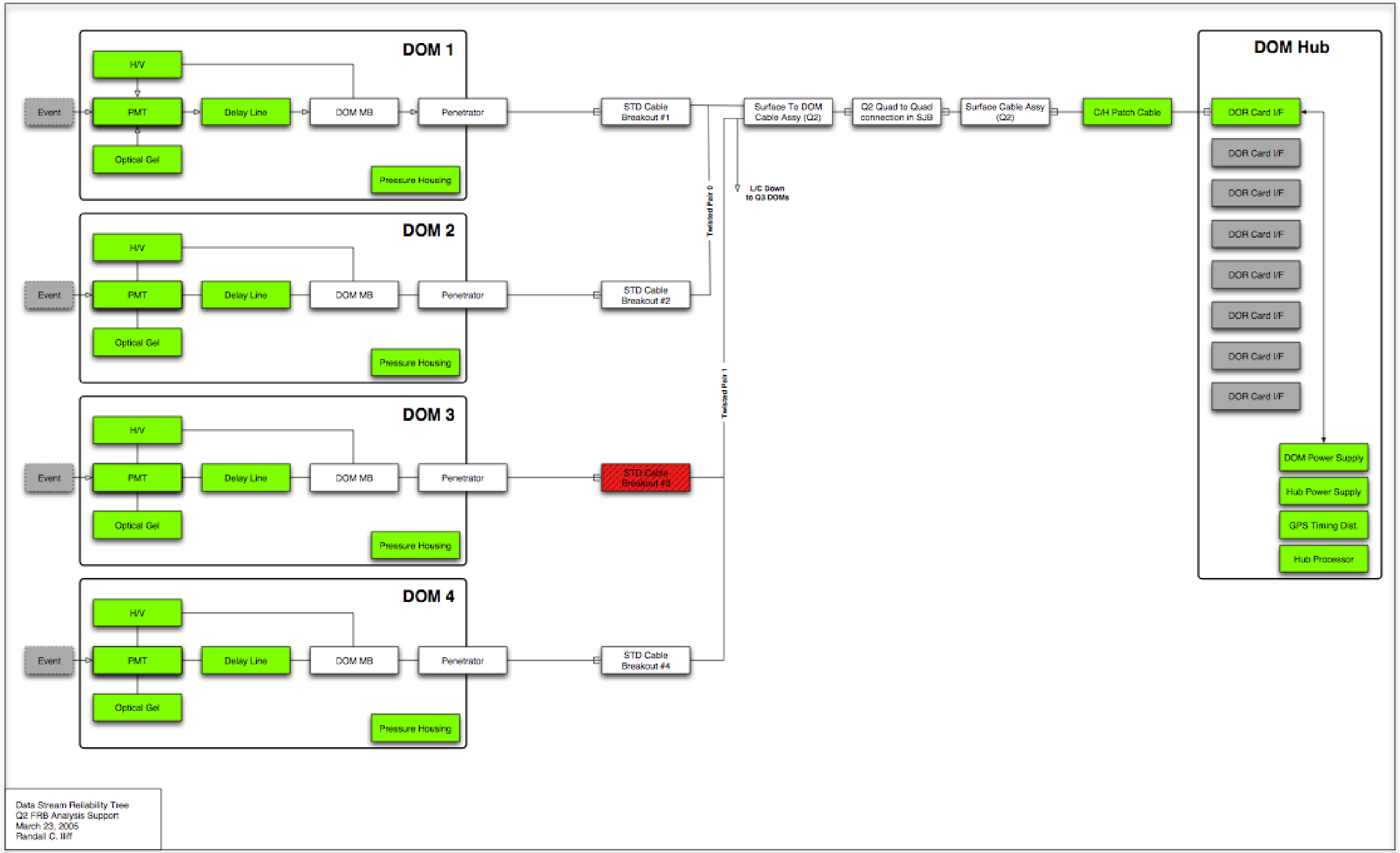


Over 5,000 Digital Optical Modules



DOMs are less accessible than spacecraft once they are deployed in deep ice.

Science Data Stream Reliability



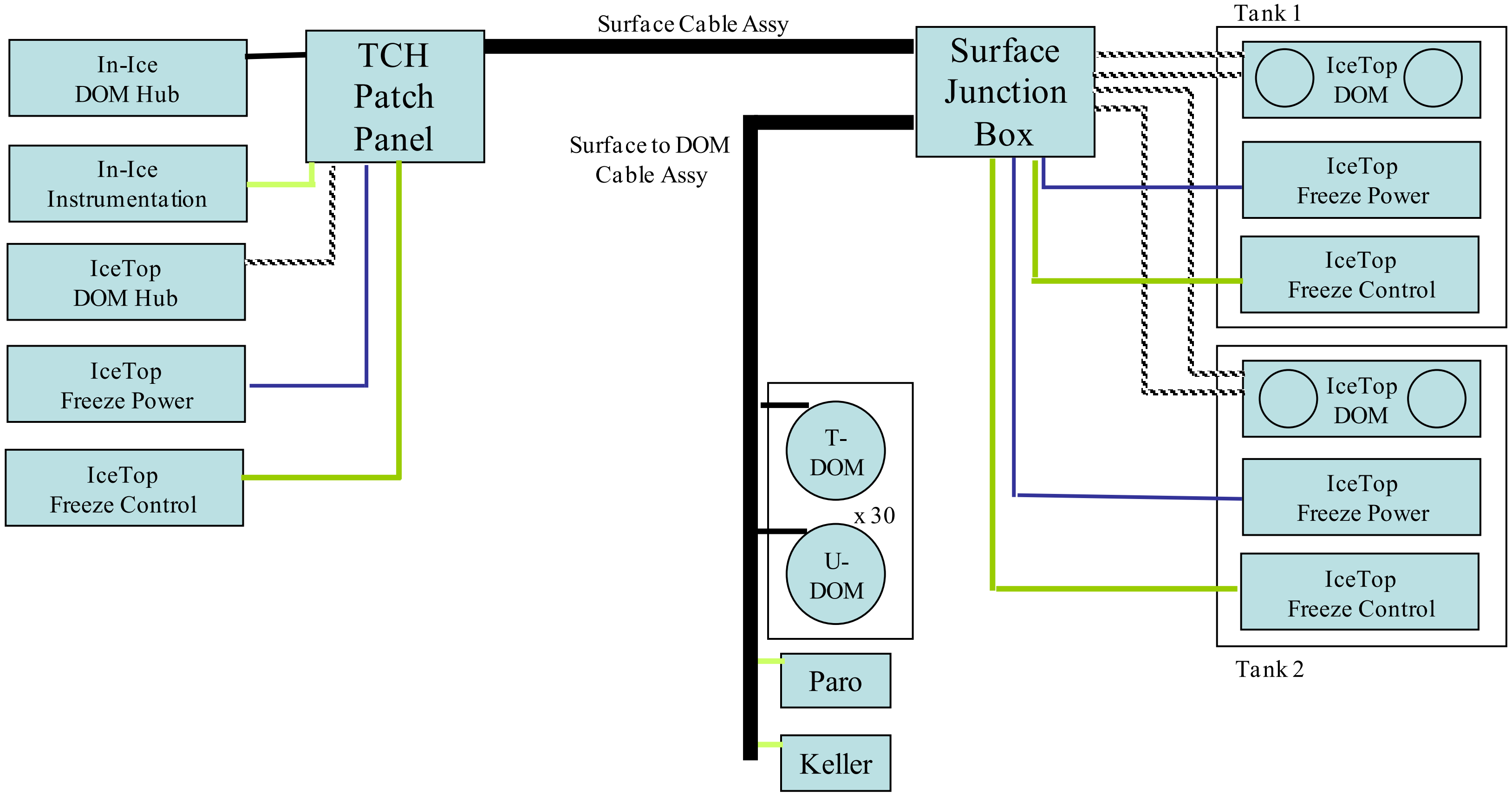
Drove FMEA / Design / Test Priority

Functional Role	Key System Elements	Accessible?	Failure Effect	Criticality
Science Data Stream - Sensor Subsystem	In-Ice and Ice-Top DOMs, cables, connections	No	Permananent Loss of Science Data due to failed Channel(s) for the remainder of the instrument operational life.	Very High
			Permananent Loss of Science Data due to induced failure of Channel(s) for the remainder of the instrument operational life.	Very High
			Permananent Loss of Science Data from Channel(s) d to wear out, performance drift, or end of service life degradation effects in excess of user defined thresholds.	High
			Degraded Science Data from Channel(s) compared w specifications, but still deemed useful for scientific purposes such as Supernova detection and reporting	Moderate
Science Data Stream - DOM Hub	DOM Hub, DOR Card, DOM Power Supply, Master Clock Distribution System	Yes	Permanent Loss of Science Data from unavailable channel(s) / string(s) during the interval between failure and system restoration following maintenance	Moderate
Buffer Limited Trigger and Event Processing	Raw Data Storage, Raw Data Buffer, String Processor, Trigger, Event Buffer, Event Data Storage, Communications Buffer	Yes	Permanent Loss of Science Data from effected channel(s) / string(s) during the interval between buffer overflow and system restoration following maintenance.	Moderate
Off-Line Data Processing	All other system elements	Yes	User inconvenience prior to restoration, no loss of science data.	Low

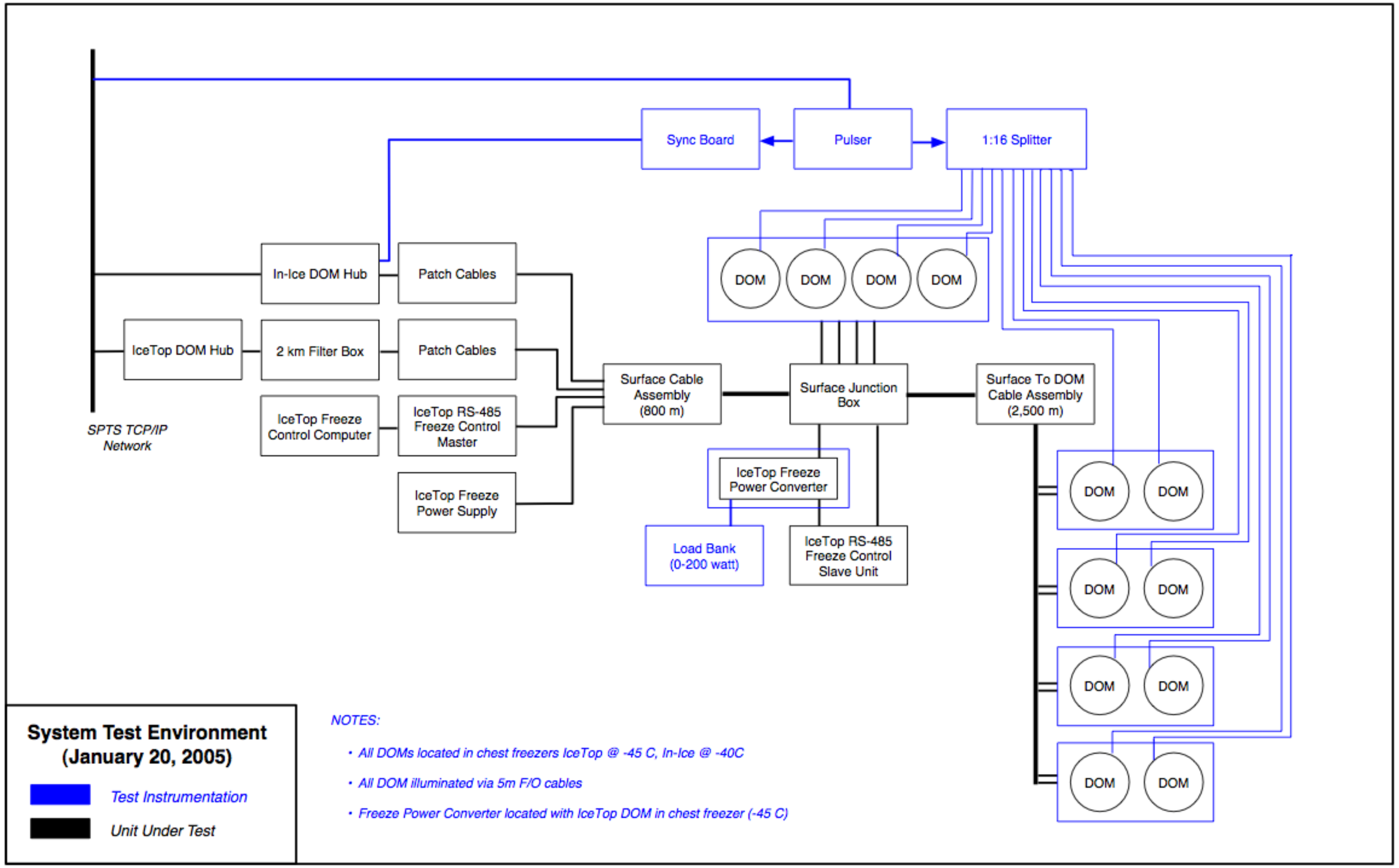
Designing the Verification System

System Test Activity	Surface Cable Assembly	Surface Junction Box	Surface to DOM Cable Assembly	IceTop DOM	T-Type In-Ice DOM	U-Type In-Ice DOM	IceTop RS-485 Simulator	IceTop Tank Power Converter	Chest Freezer Unit	Time Synchronized Light Source
Measure full path electrical characteristics	X	X	X							
Demonstrate basic operation of two In-Ice DOM on single twisted pair	X	X	X		1	1			1	
Demonstrate basic operation of four In-Ice DOM on single quad	X	X	X		2	2			2	
Demonstrate basic operation of eight In-Ice DOM on two quads	X	X	X		4	4			4	
Demonstrate basic operation of single Ice-Top DOM on twisted pair	X	X		1					1	
Demonstrate basic operation of two Ice-Top DOM on single quad	X	X		2					1	

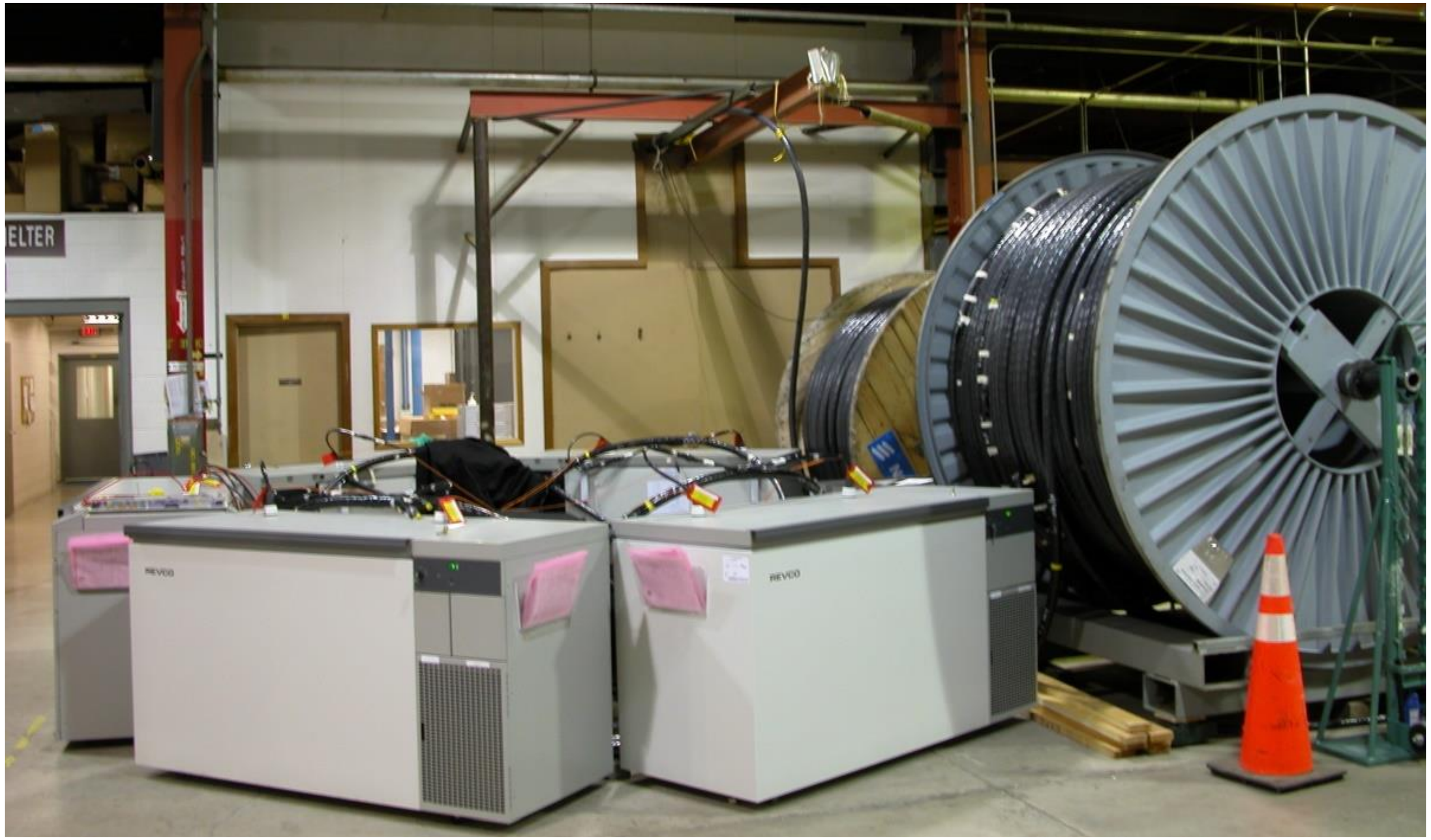
String Architecture and Interfaces



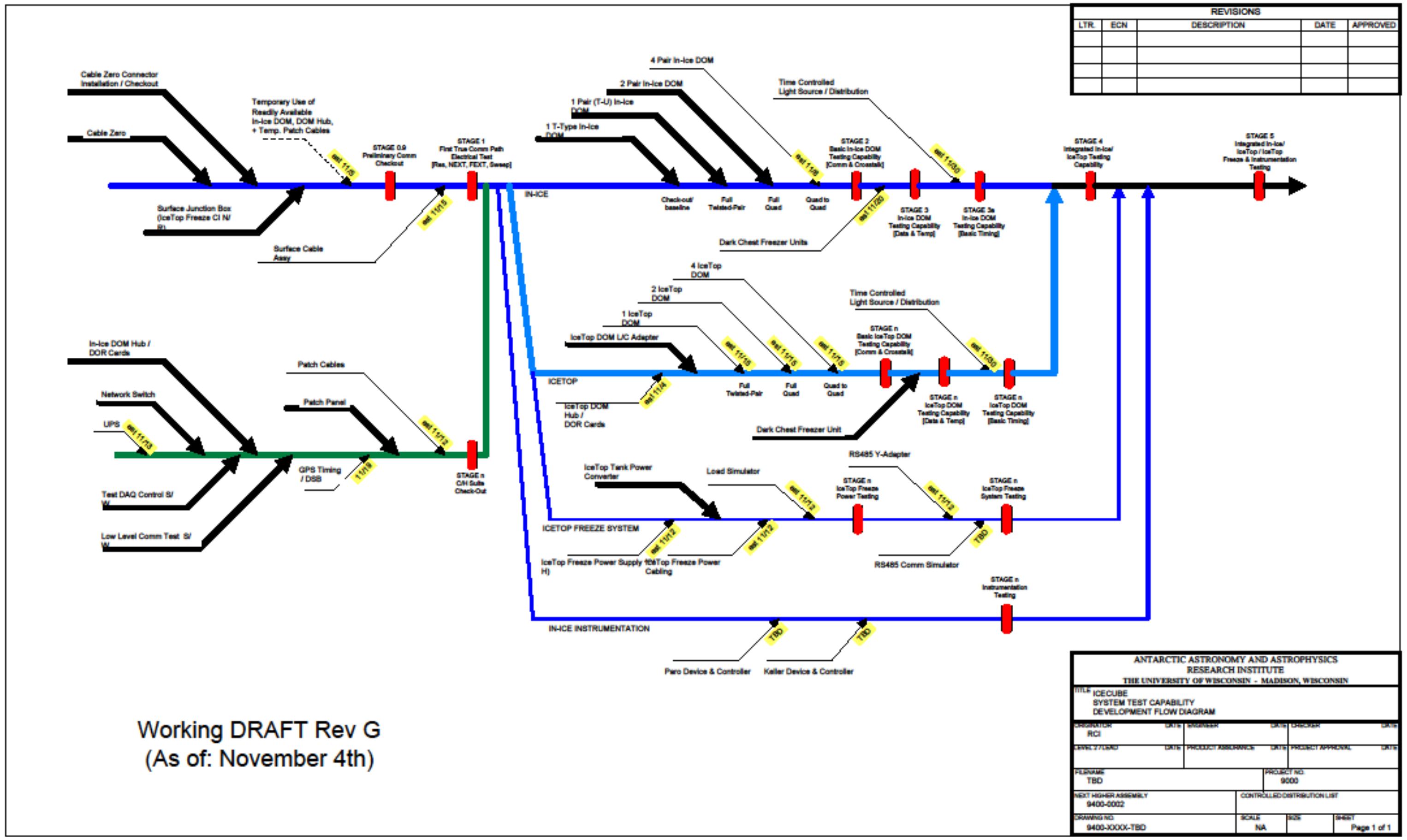
Test System Architecture and Interfaces



Setting Up the Development Test Area



System Integration / Test Planning



Development Test Conduct

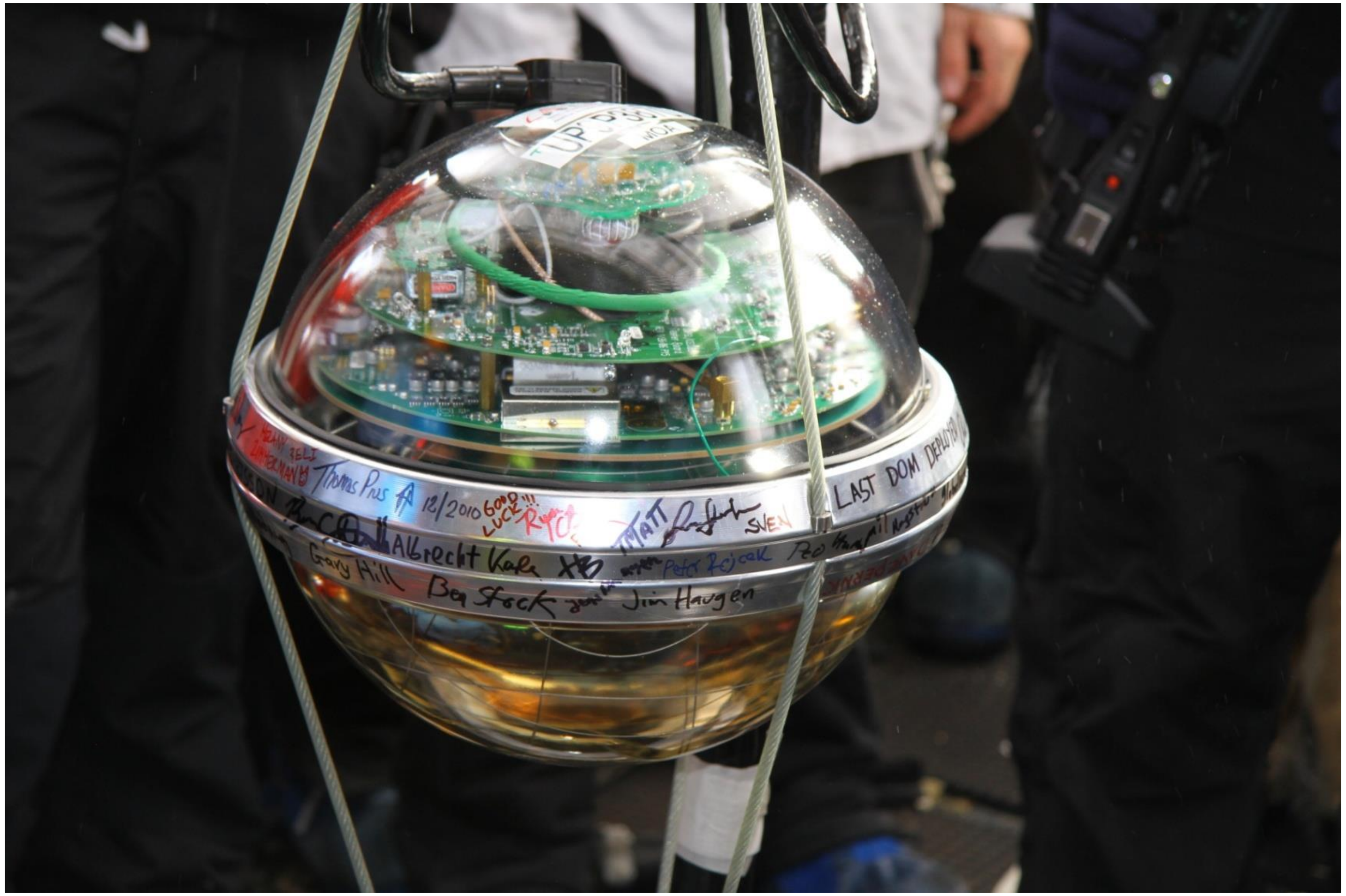
							In-Ice DOM							
Run	**Run Start**	**Duration**	**Pulser Freq**	**T-Cal Rate**	**Noise Type**	**Sync Board**	**DOM 60**	**DOM 59**	**DOM 58**	**DOM 57**	**DOM 56**	**DOM 55**	**DOM 54**	**DOM 53**
PART ONE: ESTABLISH TIMING BASELINE *Run set allows evaluation of timing impacts caused by simultaneous operation of system elements, including intra-quad, inter-quad, and In-Ice / IceTop crosstalk effects as well as compar*														
BASELINE - INITIAL OPERATIONAL CONFIGURATION (PRIOR TO ICETOP TANK FREEZE COMPLETION)														
1	1/27/2005 0:00	2 runs @ 30 min	100 Hz	.2 Hz	None	*Active*	*Active*	*Active*	*Active*	*Active*	*Active*	*Active*	*Active*	*Active*
2		2 runs @ 30 min	100 Hz	.2 Hz	None	*Active*	*Active*	*Active*	*Active*	*Active*	*Active*	*Active*	*Active*	*Active*
BASELINE - OPERATIONAL CONFIGURATION														
3		2 runs @ 30 min	100 Hz	.2 Hz	None	*Active*	*Active*	*Active*	*Active*	*Active*	*Active*	*Active*	*Active*	*Active*
BASELINE - ICETOP ONLY (FULL STATION, SINGLE TANK, SINGLE DOM)														
4		2 runs @ 30 min	100 Hz	.2 Hz	None	*Active*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*
5		2 runs @ 30 min	100 Hz	.2 Hz	None	*Active*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*
6		2 runs @ 30 min	100 Hz	.2 Hz	None	*Active*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*
BASELINE - IN-ICE ONLY (MULTIPLE QUADS, SINGLE QUAD, SINGLE PAIR, SINGLE DOM)														
7		2 runs @ 30 min	100 Hz	.2 Hz	None	*Active*	*Active*	*Active*	*Active*	*Active*	*Active*	*Active*	*Active*	*Active*
8		2 runs @ 30 min	100 Hz	.2 Hz	None	*Active*	*Active*	*Active*	*Active*	*Active*	*OFF*	*OFF*	*OFF*	*OFF*
9		2 runs @ 30 min	100 Hz	.2 Hz	None	*Active*	*Active*	*Active*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*
10		2 runs @ 30 min	100 Hz	.2 Hz	None	*Active*	*Active*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*	*OFF*

IceTop Tank Installation

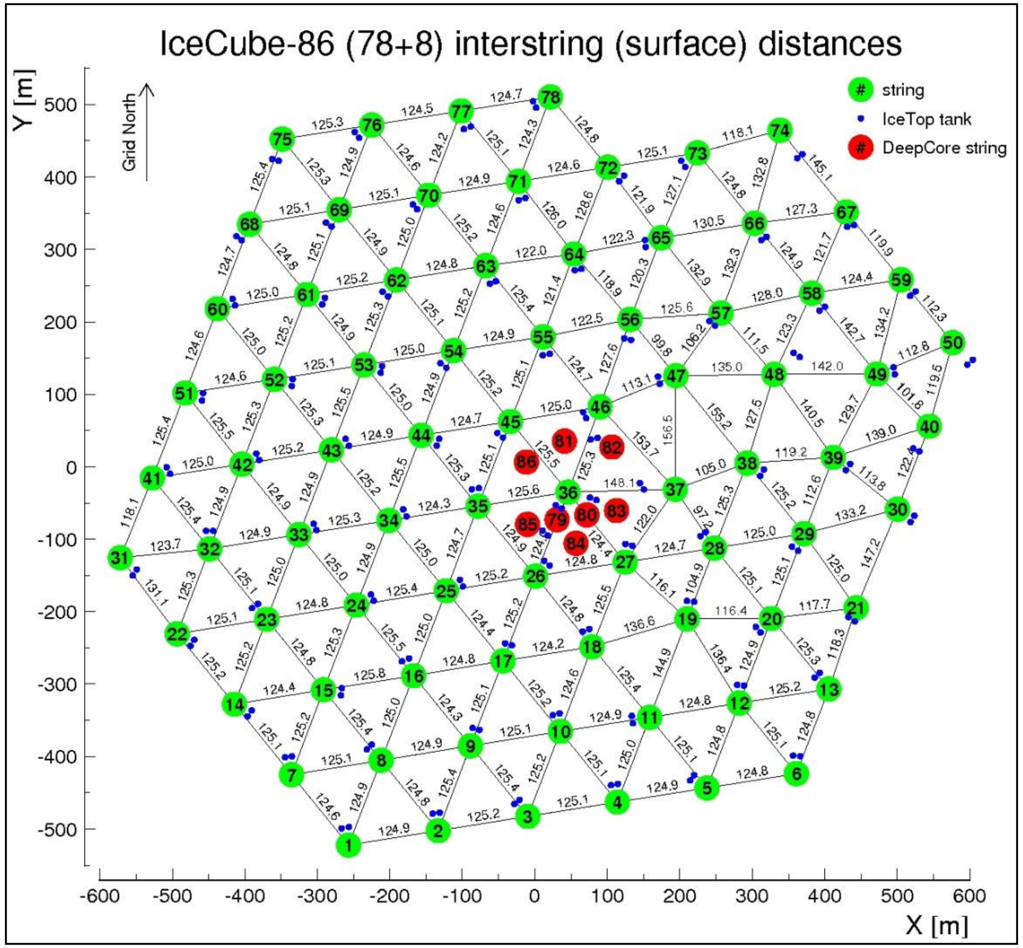
Enhanced Hot Water Drill camp

IceCube Laboratory Completed

Final DOM Installed



Final String and DOM Locations Established



On Time, On Budget, and Discovery-Class Results!

RESEARCH ARTICLE | NEUTRINO ASTROPHYSICS

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration*,†

+ See all authors and affiliations

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Space.com › Science & Astronomy

Here's Why IceCube's Neutrino Discovery Is a Big Deal

By Meghan Bartels, Space.com Senior Writer | July 12, 2018 11:01am ET

12 Jul 2018 | 16:20 GMT

The IceCube Neutrino Detector at the South Pole Hits Paydirt

A single subatomic collision has opened a new door in astronomy

By **Stephen Cass**

SCIENTIFIC AMERICAN.

SPACE

Neutrinos on Ice: Astronomers' Long Hunt for Source of Extragalactic "Ghost Particles" Pays Off

Along with gravitational waves, the find adds more options for "multimessenger" astronomy, which does not solely rely on light to gather data

By Mark Bowen on July 12, 2018

Three papers released in July (two in *Science* and one on the preprint server arXiv) announced the culmination of this 60-year quest. IceCube, a strange telescope made of deep glacial ice at the South Pole, has detected neutrinos from a distant, luminous galaxy.

Parting Thoughts

This was the largest single project in UW history

- Over $300 million from various funding agencies.
- More than 450 people involved worldwide.
- Coordination with dozens of other universities.

It is always a bitter-sweet moment to “finish” big projects:

- Intellectual and logistics challenges were fun.
- It was a fantastic team of people to work with.
- Achievements will be credited to researchers, not the engineers and project managers.

Questions?