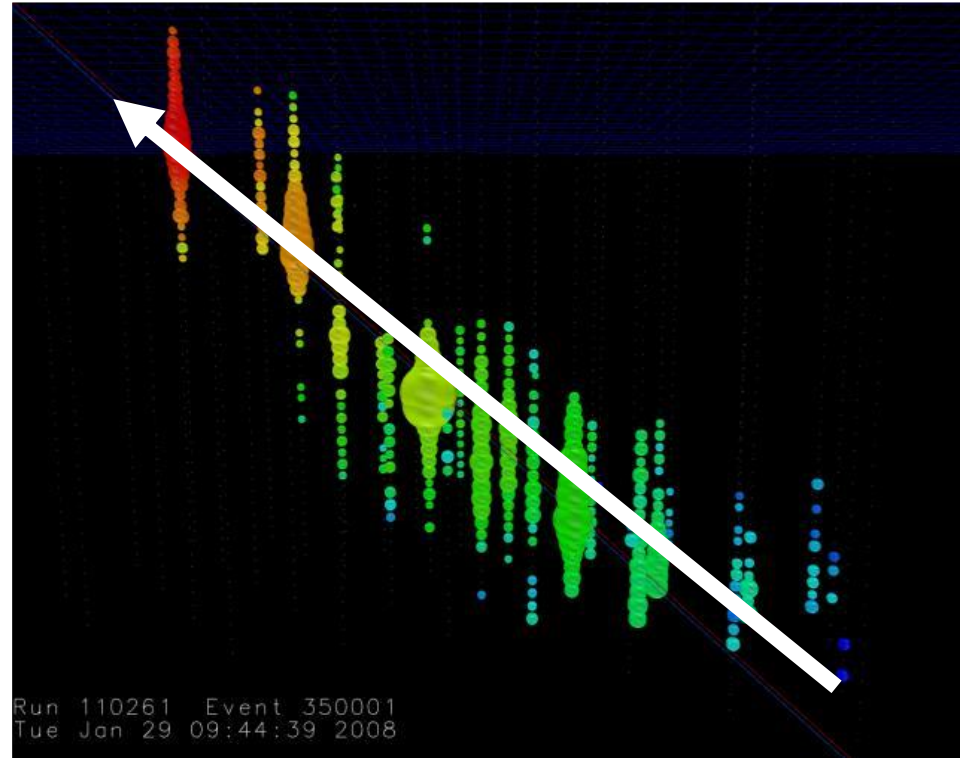


# The Invisible Matters

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

Randall C. Iliff



**Eclectic Intellect, LLC**

# Please Note

This material is based upon work supported by the National Science Foundation under Grant Numbers OPP-9980474 (AMANDA) and OPP-0236449 (IceCube).

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?

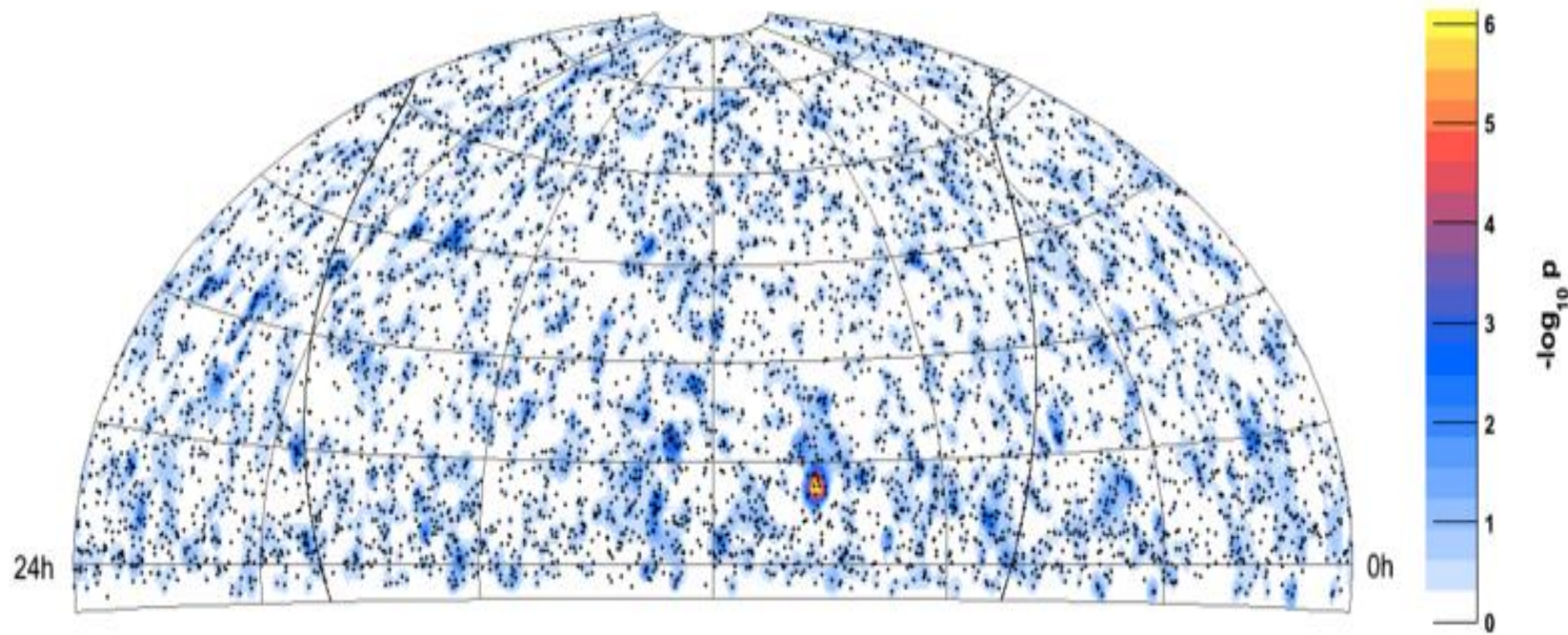
- “IceCube” is a cubic kilometer, gigaton scale Discovery Class research instrument now operating at the South Pole.
- IceCube is a unique telescope, able to look in all directions at once.
- Instead of light, this telescope captures ghostly, virtually undetectable subatomic particles known as neutrinos.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

# So, What's a Neutrino?

- Neutrinos are the 2<sup>nd</sup> 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.

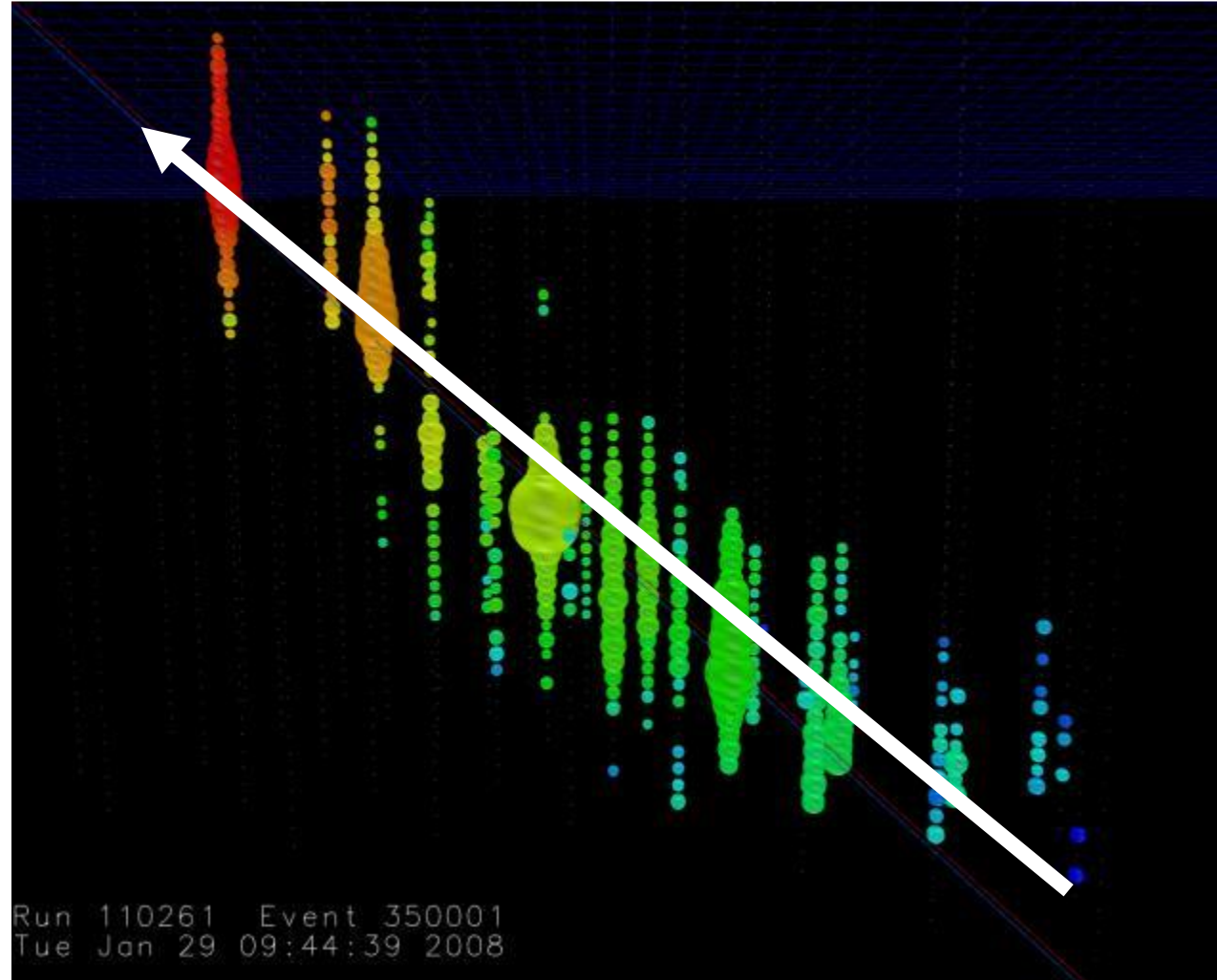
# Where do Neutrinos Come From?

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

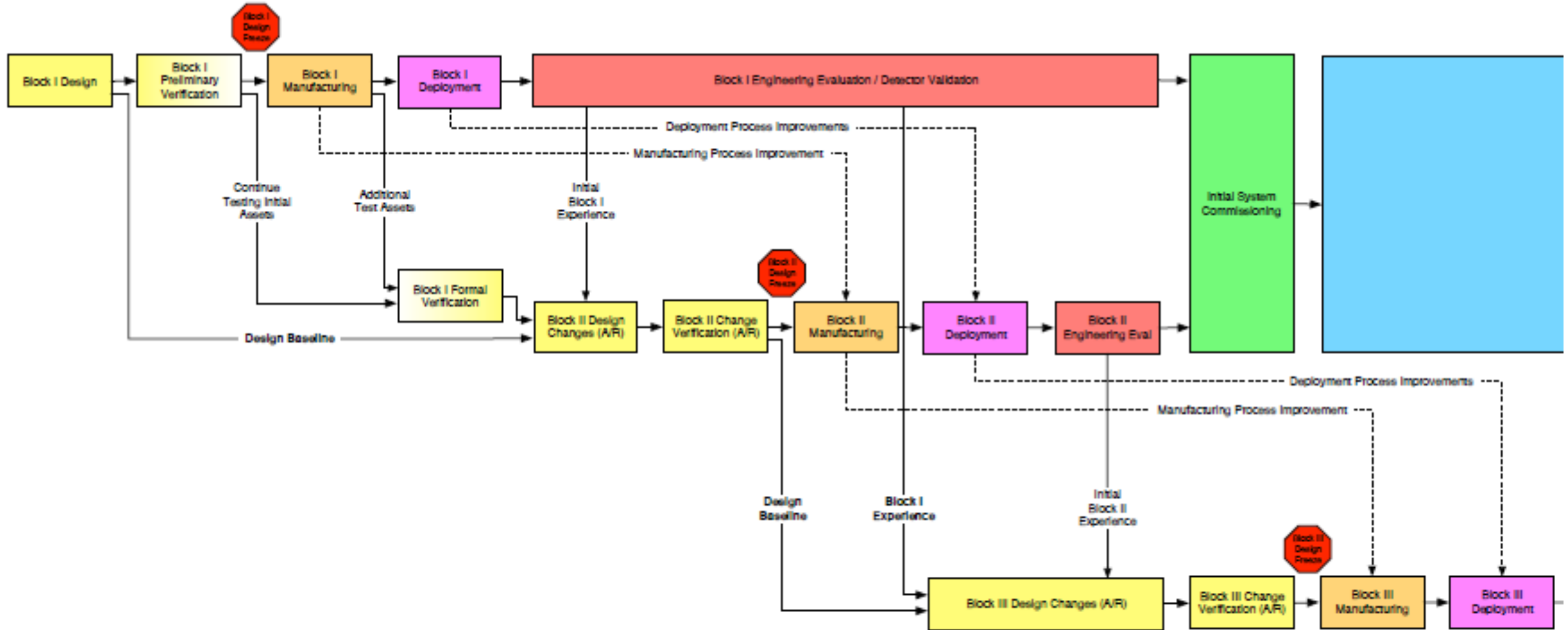
- The Technical Dimension:
  - Operational and support requirements.
  - Extreme environmental conditions.
  - Need for spacecraft level reliability.
- Tailoring SE to Function in an Academic Setting:
  - Role was externally imposed upon the project.
  - Very limited SE awareness or buy-in.
  - Prior work patterns and relationships remained dominant.



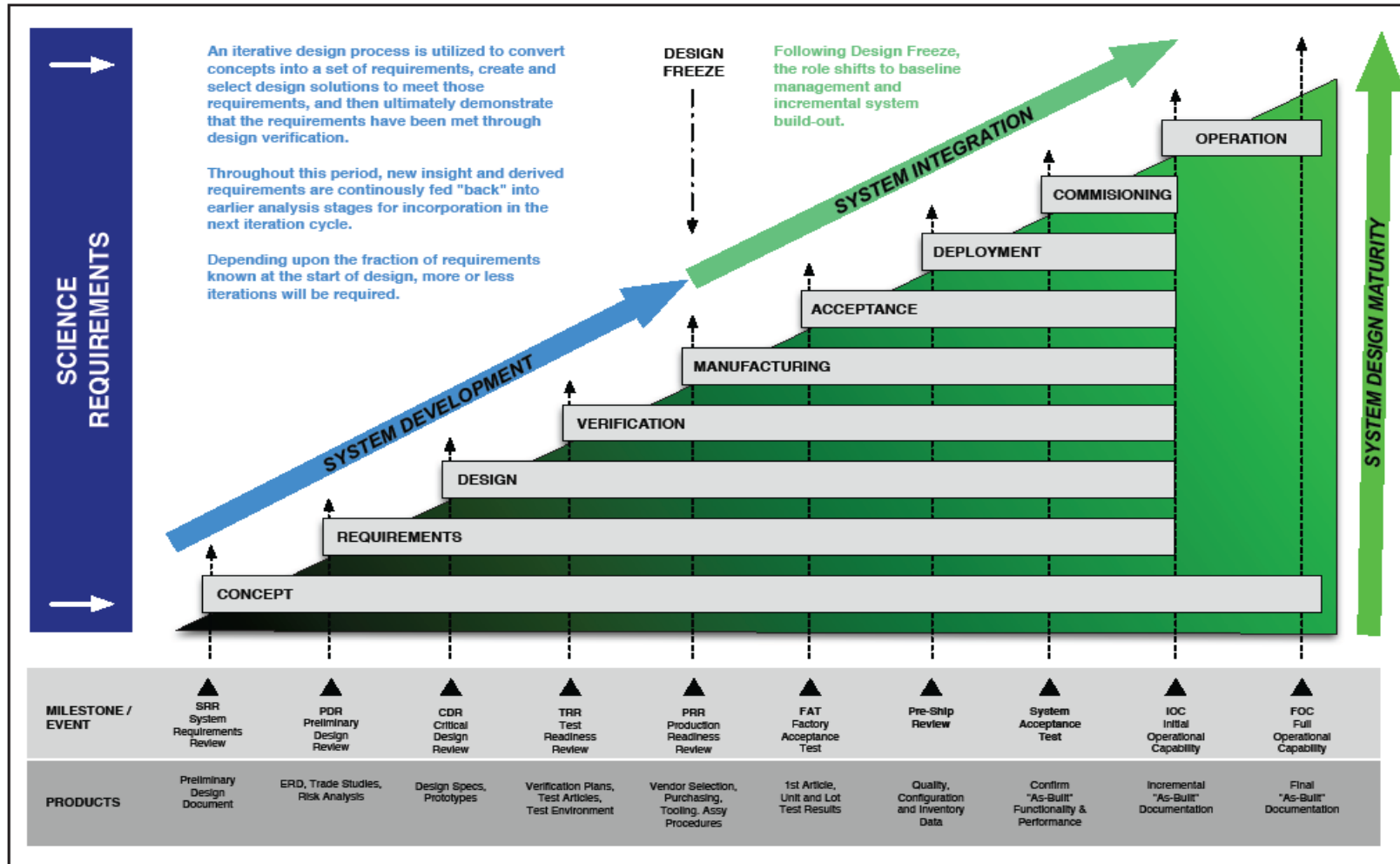
# Plus Working at the South Pole...



# Development Leapfrog Required



# Simplified Systems Engineering Process



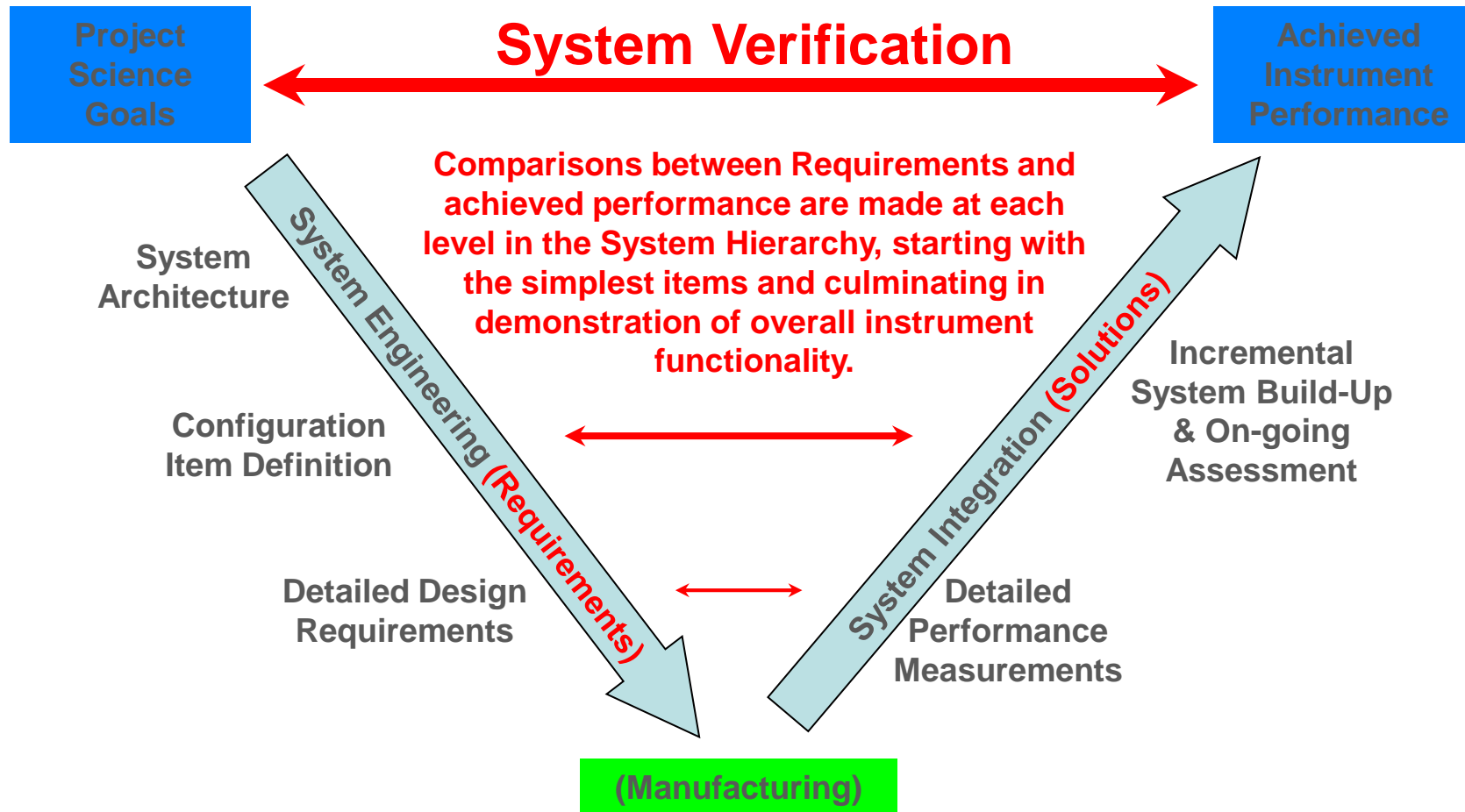
# Overall Requirements Determined and Allocated to CIs

FUNCTION	SCIENCE OBJECTIVES - THE KICQUE "MISSION"						SUBSYSTEM ALLOCATION						
	Search for sources of cosmic rays that generate resonances	Search for steady and variable sources of high energy neutrinos, e.g. Active Galactic Nuclei or Supernovae Remnants	Search for high energy neutrinos from transient sources such as Gamma Ray Bursts and Supernovae Bursts	Search for neutrinos from the decay of superheavy particles related to topological defects	Search for WIMPs which may constitute dark matter	Search for magnetic monopoles and other exotic particles like strange quark matter	Monitor our Galaxy for Solar neutrinos from Solar flares, eruptions and operation noise (SNEDEC)	Search for unexpected phenomena	Sensor Subsystems	At-Center Laboratory (PCL)	South Hemisphere Data Center	Software Subsystems	Enabling Systems
<b>PRIMARY SCIENCE REQUIREMENTS</b>	Event Energy Range	TaV to PaV	TaV	to 100 TeV	PaV to EaV	To GaV to PaV	TBD eV	MeV	TBD eV				
	Expected Detectable Event Rate	TBD events/yr	TBD events/yr	"year" to 100 events/kyr	1 to 100 events/kyr	TBD events/yr	TBD events/yr	TBD events/yr	TBD events/yr				
	Desired Angular Resolution	< 1 degree at TBD eV (Driven by desire to resolve the specific cosmological source)		TBD Degrees (Do we care what they are just being able to have sufficient data for overall event reconstruction?)			N/A		TBD degrees				
	Weather	sufficient duration / resolution to distinguish event signatures (TBD re duration, TBD dynamic range, TBD sample rate)							1 to 3 ms <sup>2</sup>	TBD s			
	Time Resolution	5 - 10 ns with initial degradation experienced at lower event energies							1 to 3 ms <sup>2</sup>	TBD			
	Operating Life	Fifteen year restoration design life allows for 10 year fully configured operational period plus multi-year deployment.											
<b>PRIMARY SYSTEM REQUIREMENTS</b>	Instrumented Ice Volume	1 cubic kilometer (nominal)											
	Active Stron	Polyhedral consisting of parallel upper and lower planes with horizontal cross section.											
	Effective Volume	TBD cubic kilometer at TBD eV and TBD axial angle (batter with energy level and event orientation)											
	Number of Strings	80											
	Digital Central Modules (DCM) per String	80											
	Total Number of DCM	4000											
	DCM Spacing - Horizontal	120 meters (offset means to instrument the required volume of ice, provides good resolution for higher energy levels)											
	DCM Spacing - Vertical	16.7 meters (provides highest resolution for vertical tracking particles)											
	Detector Depth	1400 - 2400 meters (optical properties of ice improve with depth, limiting factor is boundary to surface shower effects)											
	Total Station Count	1 halfTop station at each hole location, normally 80 station sets											
	Tanks per Station	2 tanks at each station provide operational redundancy, local veto capability											
	Effective Tank Volume	(TBD) sample look up and read rates											
	Digital Central Modules (DCM) per Station / Tank	Two DCM in each tank are used to provide greater dynamic range, resulting in a total of four DCM per halfTop Station set.											
	Total Number of DCM	320											
	DCM Spacing - Horizontal	Within the tanks, spacing is 1 meter.											
	DCM Spacing - Vertical	halfTop array is positioned roughly 1,400 meters above the topmost in-ice DCM.											
	Detector Depth	Tanks are installed to be flush with grade when covered, additional snow accumulation at roughly 1 foot per year threshold.											
<b>SECONDARY SYSTEM REQUIREMENTS</b>	Sensitivity of DCM	Single Photo Event (SPE)											
	DCM Photon Error Dynamic Range	SPE > 300 PE / 15 ns. (Note: two DCM are used in a high - low gain mode to support the halfTop Dynamic Range Requirement.)											
	DCM Field of View	Hemispherical with TBD fov (TBD set out)											
	Digitization Rate	300 megasamples / second											
	Triggering Rate	40 megasamples / second											
	Timing Accuracy	< 5 ns											
<b>OPERATIONAL REQUIREMENTS</b>	Establish DCM Physical Location	Determine x, y, z coordinates to within 5 Meter (TBD)											
	Establish special characteristics of ice along all lines of DCM path	Primary path loss, although scattering and other effects may also be noted.											
	Establish operating characteristics of each DCM	Gain, noise rate, FOV, spectral characteristics, others.											
	String Commissioning	Determine that newly deployed string is acceptable to add to the body of operational instruments.											
<b>ENVIRONMENTAL REQUIREMENTS</b>	DCM Noise Rate	< 800 hits / second											
	DCM Data Processing	Initial waveform capture and digitization in DCM, convert sensitive compression of data prior to transfer.											
	Local Coincidence Function	User selectable, three modes: OR Set - Reduced data set for marginal probability events; Hard - Discriminator function requiring "n of n" confirmation from vertically adjacent DCM.											
	Event Trigger Function	String and Global trigger logic to package event data and discriminate noise.											
	Veto Function	Surface Array (SA) allows identification and discrimination of overlapping background.											
	Warning Data Stream from Sensor Array	100 Gb / day											
	Non-Volatile Storage at South Pole	TBD Buffer / Archive Capacity & Redundancy Requirements.											
	South Pole High Priority Communications	At all times, it must be possible to complete a minimum 1000 transfer to the Northern Hemisphere within 10 minute period, (DME V/C and GPS Reporting)											
	South Pole Medium Priority Communications	500 Mb / day											
	South Pole High Volume Data Transfer	31 Gb / day											
	Northern Hemisphere Data Warehouse	TBD Buffer / Archive Capacity & Redundancy Requirements.											
	Power	Essential to minimize South Pole power consumption wherever practical.											
	Master Time Reference	Internal reference consistent with overall site timing error budget allocation, connection to UTC based on GPS reference.											
	Equipment Monitoring	Built in monitoring capabilities are essential for managing inaccessible devices (such as the DCMs) but also help minimize South Pole hardware needs.											
	Equipment Control	Equipment control is needed to manage the state of individual system elements as well as clearly establish and control operational parameters during a gran data taking session.											
	Personnel Safety	Safety is a universal design consideration, but particularly for operations that must be conducted under difficult working conditions at the South Pole.											
	Instrument Security	On site and remote access controls, user account management, and general IT safeguards to ensure undisturbed operation.											
	Data Integrity	"Chain of custody" confidence in data from first capture through analysis and publication.											
	System Growth Provisions	As a discrete instrument, there is a greater than normal responsibility to provide future flexibility for expansion or reconfiguration.											

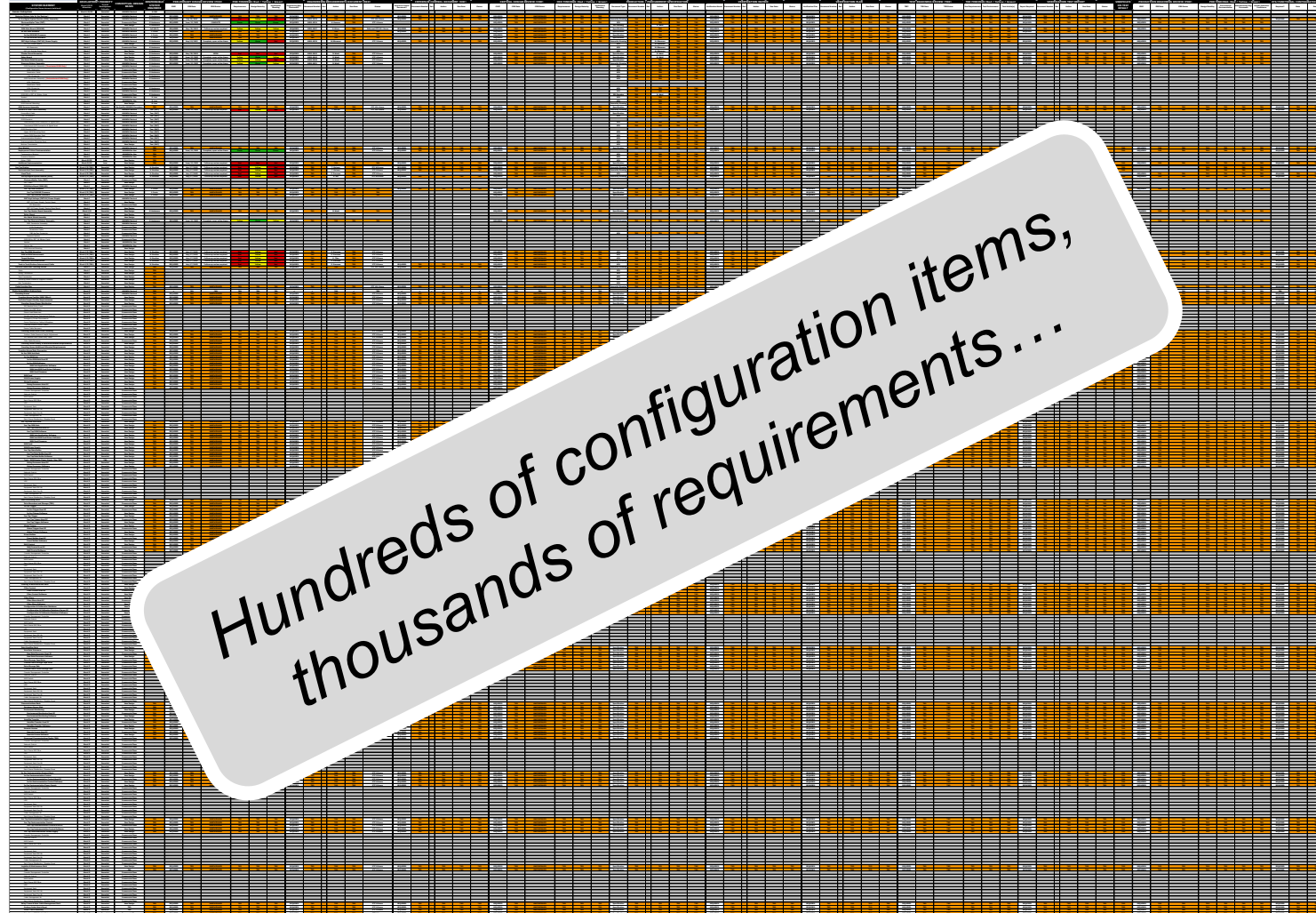
FUNCTION	PHYSICAL SUBSYSTEM ALLOCATION											
	At-Center Laboratory (PCL)	South Hemisphere Data Center	Software Subsystems	Enabling Systems	Instrumentation	DCM	DCM	DCM	DCM	DCM	DCM	DCM
Instrumented Ice Volume												
Active Stron												
Effective Volume												
Number of Strings												
Digital Central Modules (DCM) per String												
Total Number of DCM												
DCM Spacing - Horizontal												
DCM Spacing - Vertical												
Detector Depth												
Total Station Count												
Tanks per Station												
Effective Tank Volume												
Digital Central Modules (DCM) per Station / Tank												
Total Number of DCM												
DCM Spacing - Horizontal												
DCM Spacing - Vertical												
Detector Depth												
Sensitivity of DCM												
DCM Photon Error Dynamic Range												
DCM Field of View												
Digitization Rate												
Triggering Rate												
Timing Accuracy												
Establish DCM Physical Location												
Establish special characteristics of ice along all lines of DCM path												
Establish operating characteristics of each DCM												
String Commissioning												
DCM Noise Rate												
DCM Data Processing												
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Veto Function												
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Equipment Monitoring												
Equipment Control												
Personnel Safety												
Instrument Security												
Data Integrity												
System Growth Provisions												

# Emphasis on System Verification





# Results in a Lot of Stuff to Track!



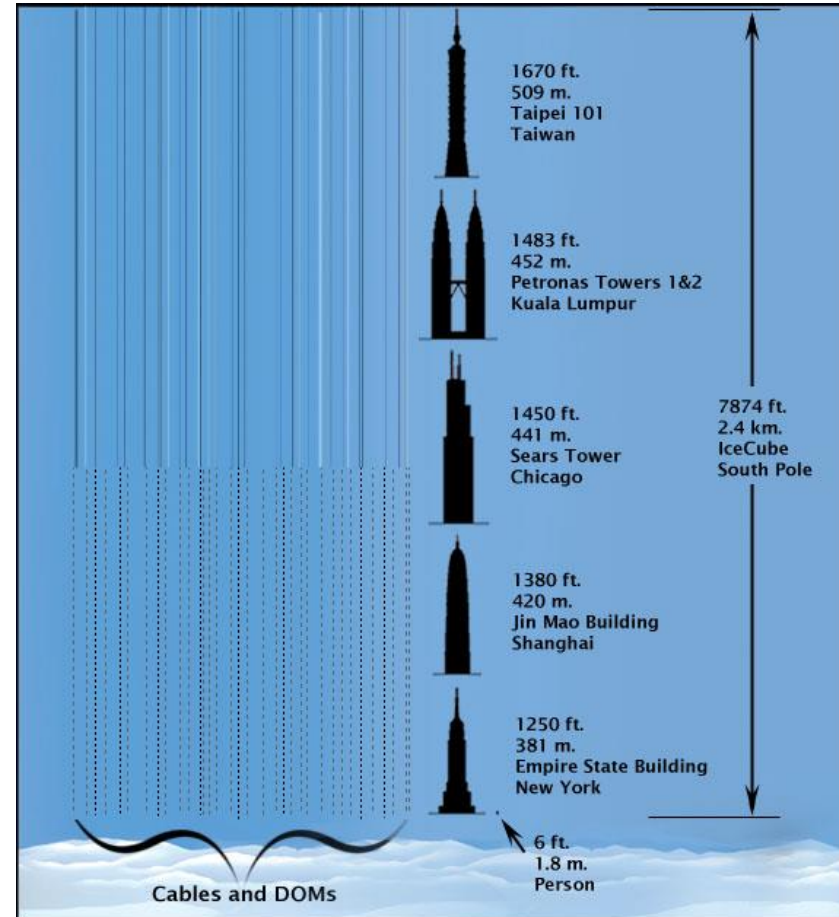
The image shows a screenshot of a data table with a grid of columns and rows. The table is filled with data, and a callout box is overlaid on it. The callout box contains the text: "Hundreds of configuration items, thousands of requirements...".

Hundreds of configuration items,  
thousands of requirements...

# Over 5,000 Digital Optical Modules

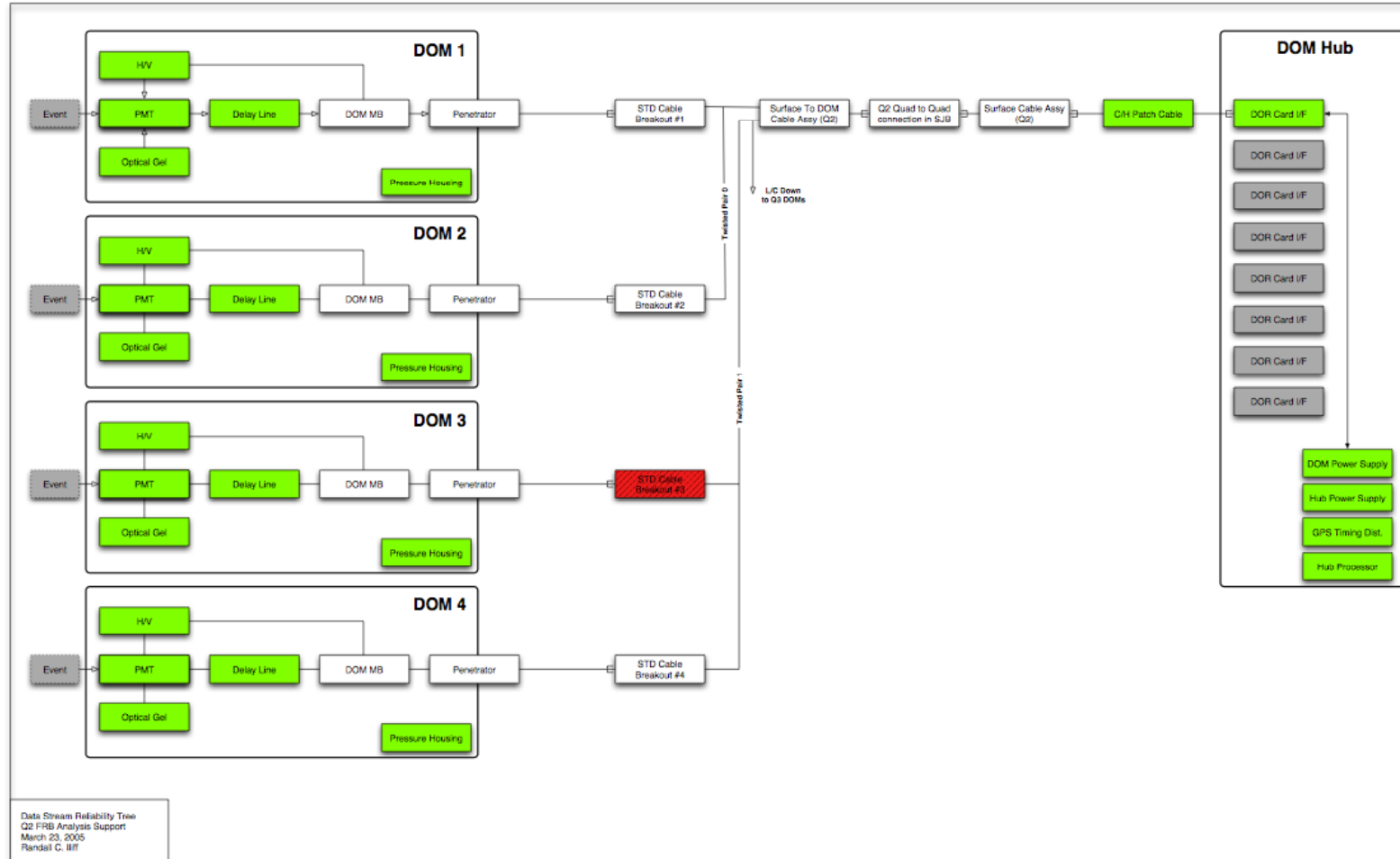


*DOMs are less accessible than spacecraft once they are deployed in deep ice.*





# Science Data Stream Reliability



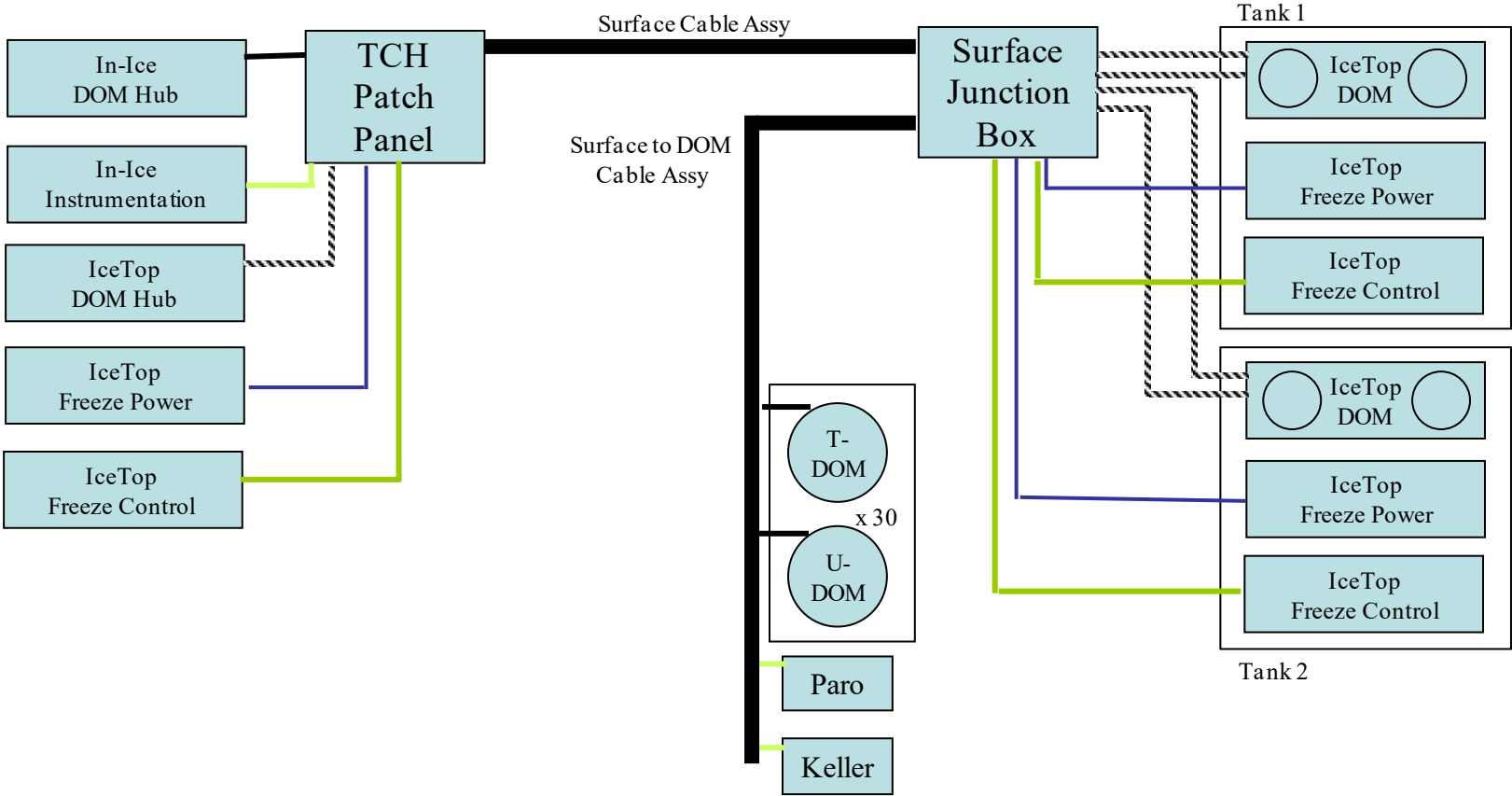
# Drove FMEA / Design / Test Priority

Functional Role	Key System Elements	Accessible?	Failure Effect	Criticality
Science Data Stream - Sensor Subsystem	In-Ice and Ice-Top DOMs, cables, connections	No	Permanent Loss of Science Data due to failed Channel(s) for the remainder of the instrument operational life.	Very High
			Permanent Loss of Science Data due to induced failure of Channel(s) for the remainder of the instrument operational life.	Very High
			Permanent Loss of Science Data from Channel(s) due 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 to 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

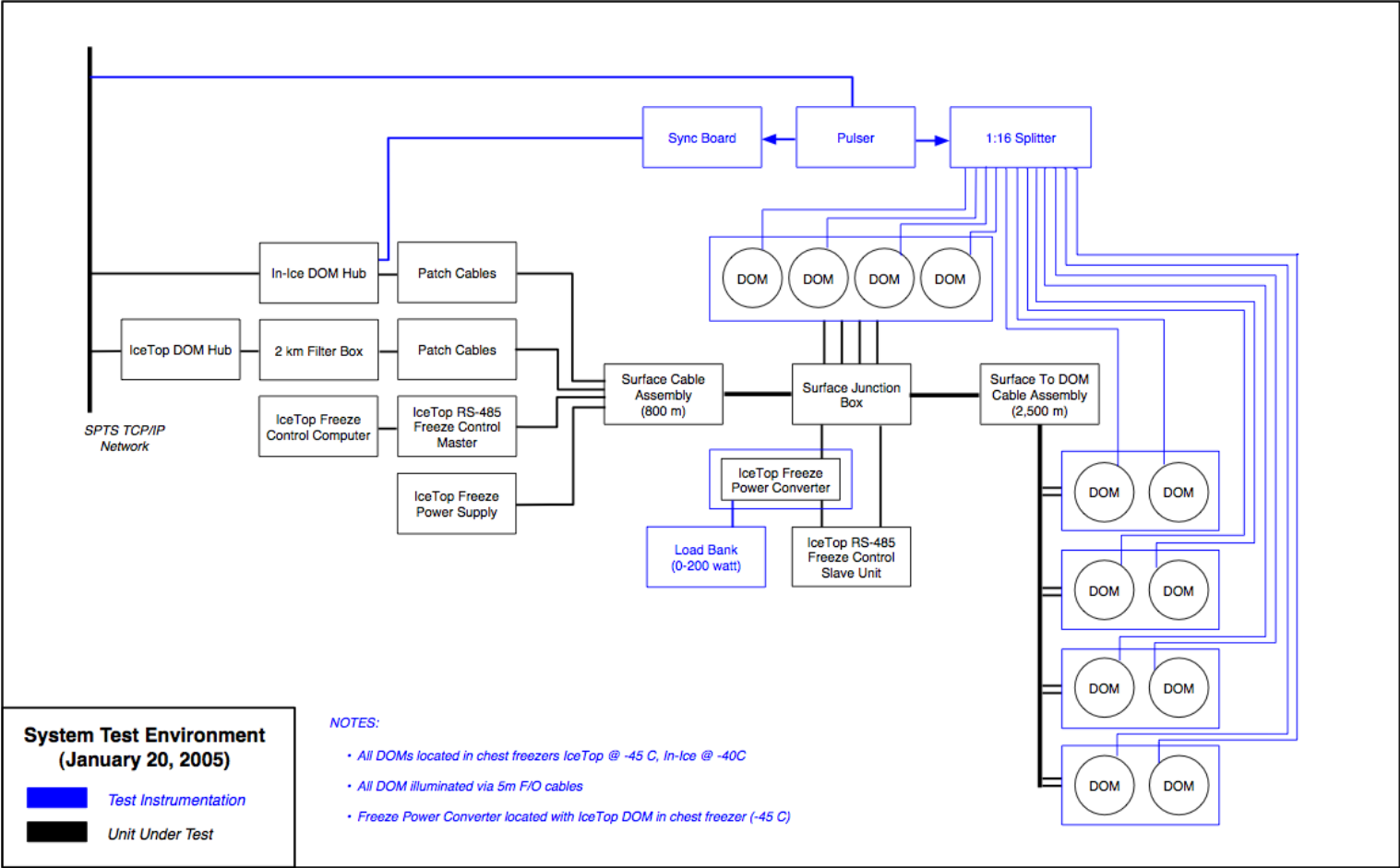
# Designing the Verification System

<b>System Test Activity</b>	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	

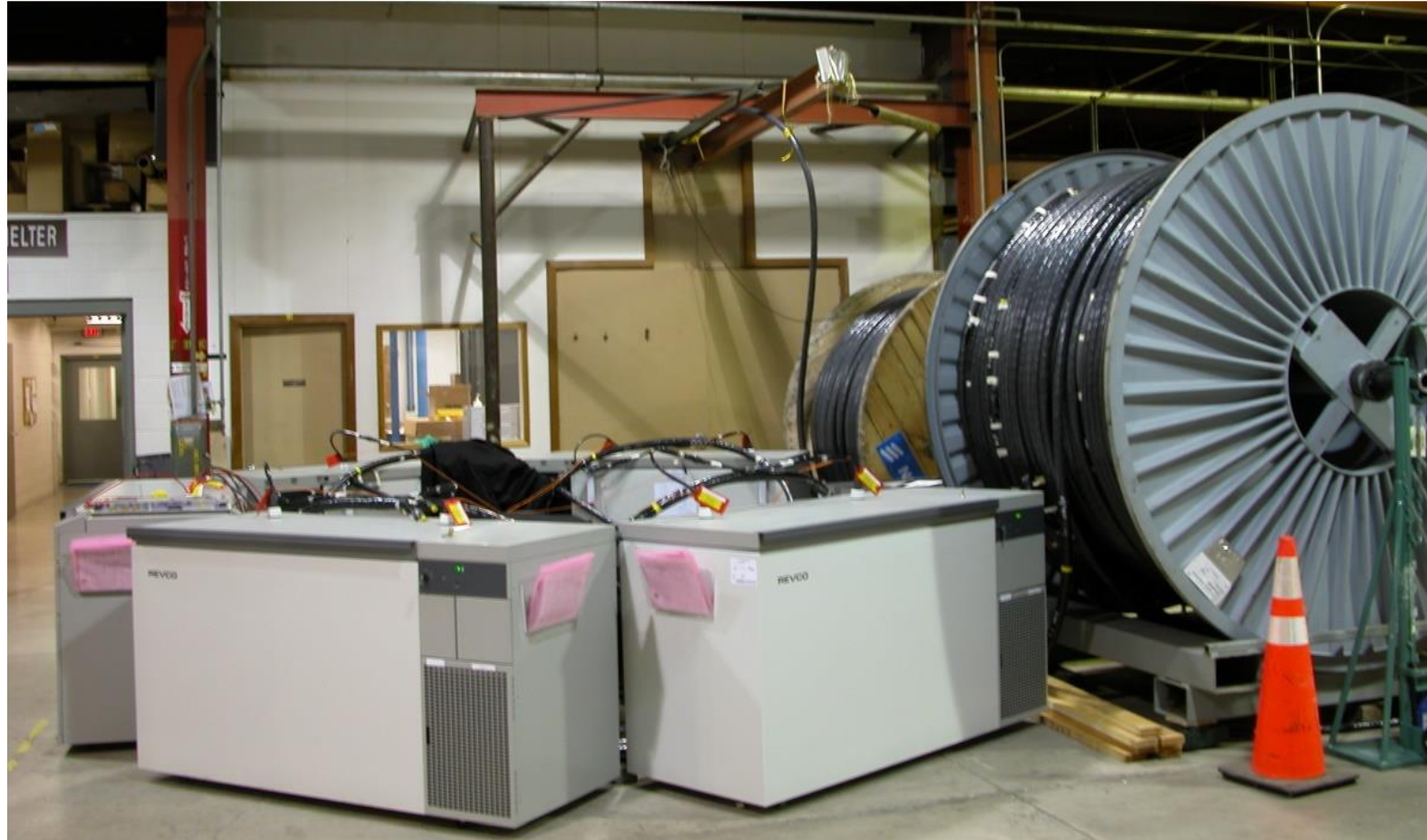
# String Architecture and Interfaces



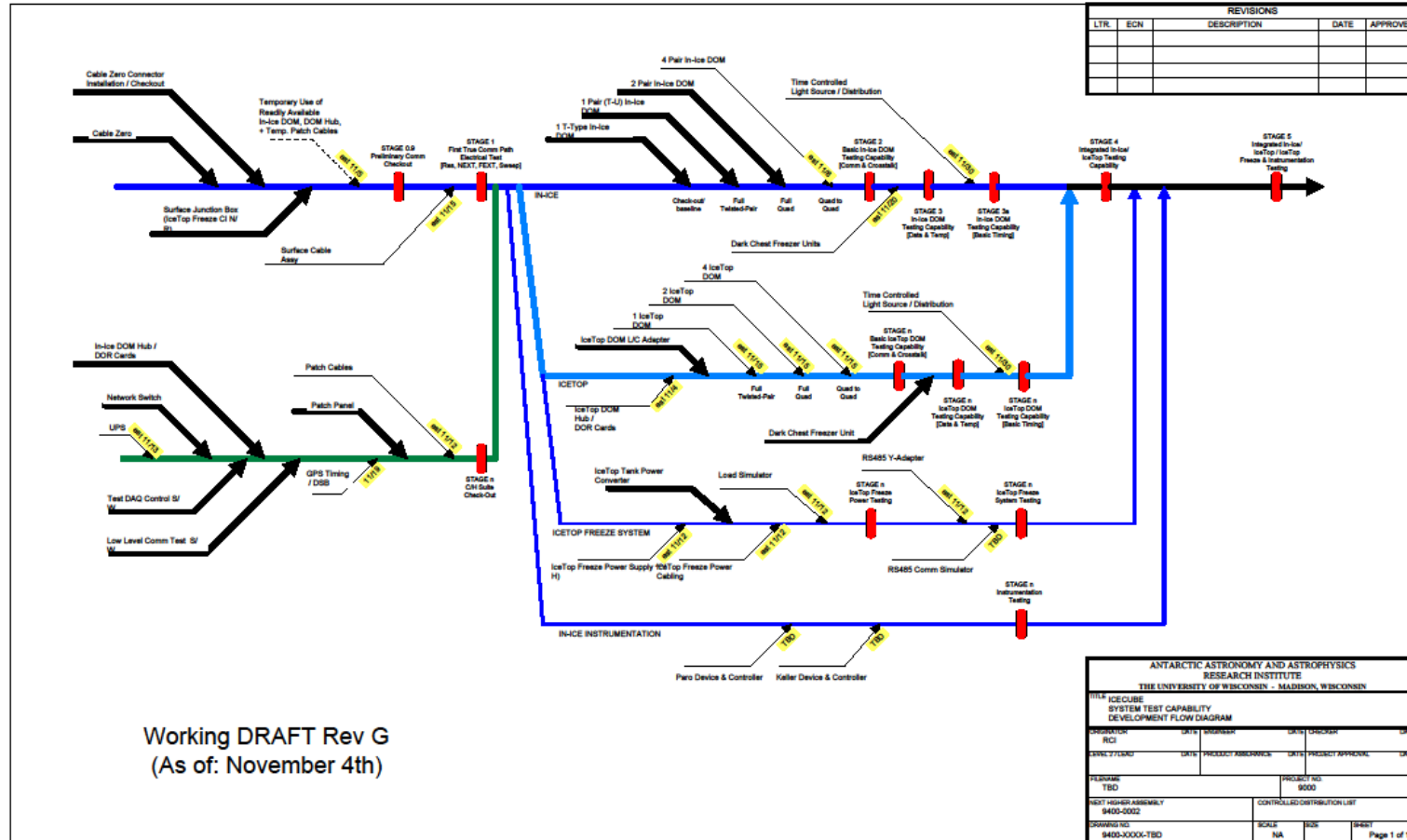
# Test System Architecture and Interfaces



# Setting Up the Development Test Area



# System Integration / Test Planning



Working DRAFT Rev G  
(As of: November 4th)



# Development Test Conduct

Run	Run Start	Duration	Pulser Freq	T-Cal Rate	Noise Type	Sync Board	In-Ice DOM							
							DOM 60	DOM 59	DOM 58	DOM 57	DOM 56	DOM 55	DOM 54	DOM 53
<b>PART ONE: ESTABLISH TIMING BASELINE</b>														
<i>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</i>														
<b>BASELINE - INITIAL OPERATIONAL CONFIGURATION (PRIOR TO ICETOP TANK FREEZE COMPLETION)</b>														
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
<b>BASELINE - OPERATIONAL CONFIGURATION</b>														
3		2 runs @ 30 min	100 Hz	.2 Hz	None	Active	Active	Active	Active	Active	Active	Active	Active	Active
<b>BASELINE - ICETOP ONLY (FULL STATION, SINGLE TANK, SINGLE DOM)</b>														
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
<b>BASELINE - IN-ICE ONLY (MULTIPLE QUADS, SINGLE QUAD, SINGLE PAIR, SINGLE DOM)</b>														
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

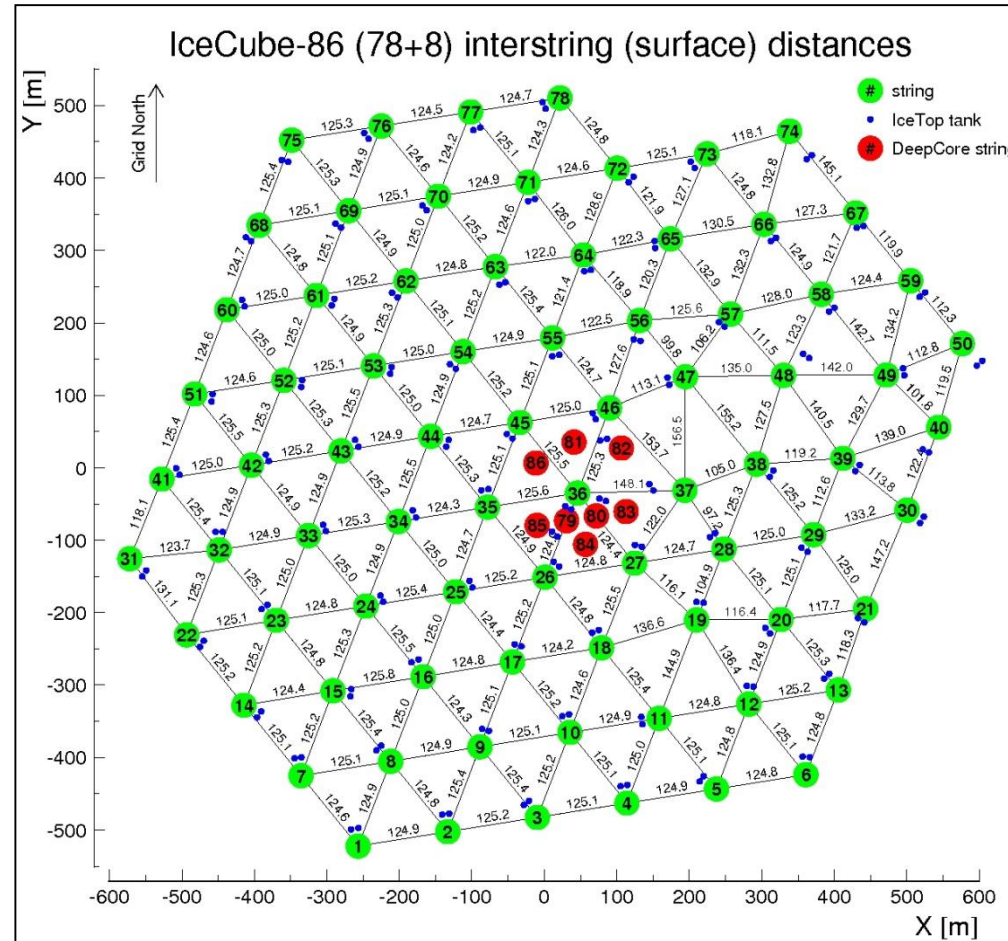




# Final DOM Installed



# 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<sup>\*,†</sup>

+ See all authors and affiliations

Science 12 Jul 2018:  
eaat2890  
DOI: 10.1126/science.aat2890

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?