IceCube Upgrade
Comms, Power, Timing Systems

Tyce DeYoung
WBS 1.4

ICNO/Upgrade Project - NSF Site Visit Review
March 17, 2020

IceCube Upgrade

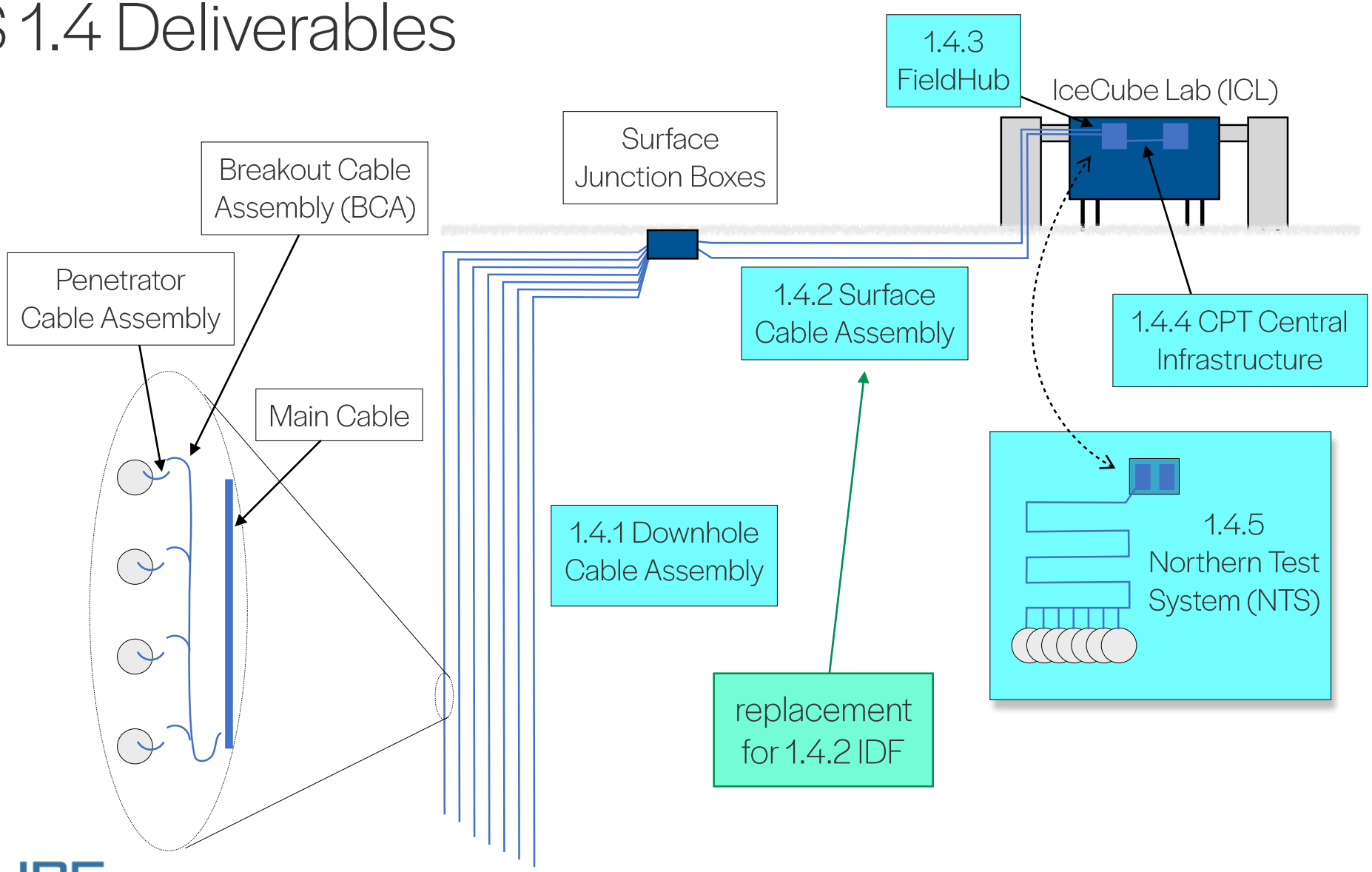
Outline

- Scope, organization, deliverables, requirements
- Schedule and milestones
- Costs and in-kind contributions
- Risks and mitigation strategies
- Technical progress
- Review schedule
- Issues and Challenges
- Summary

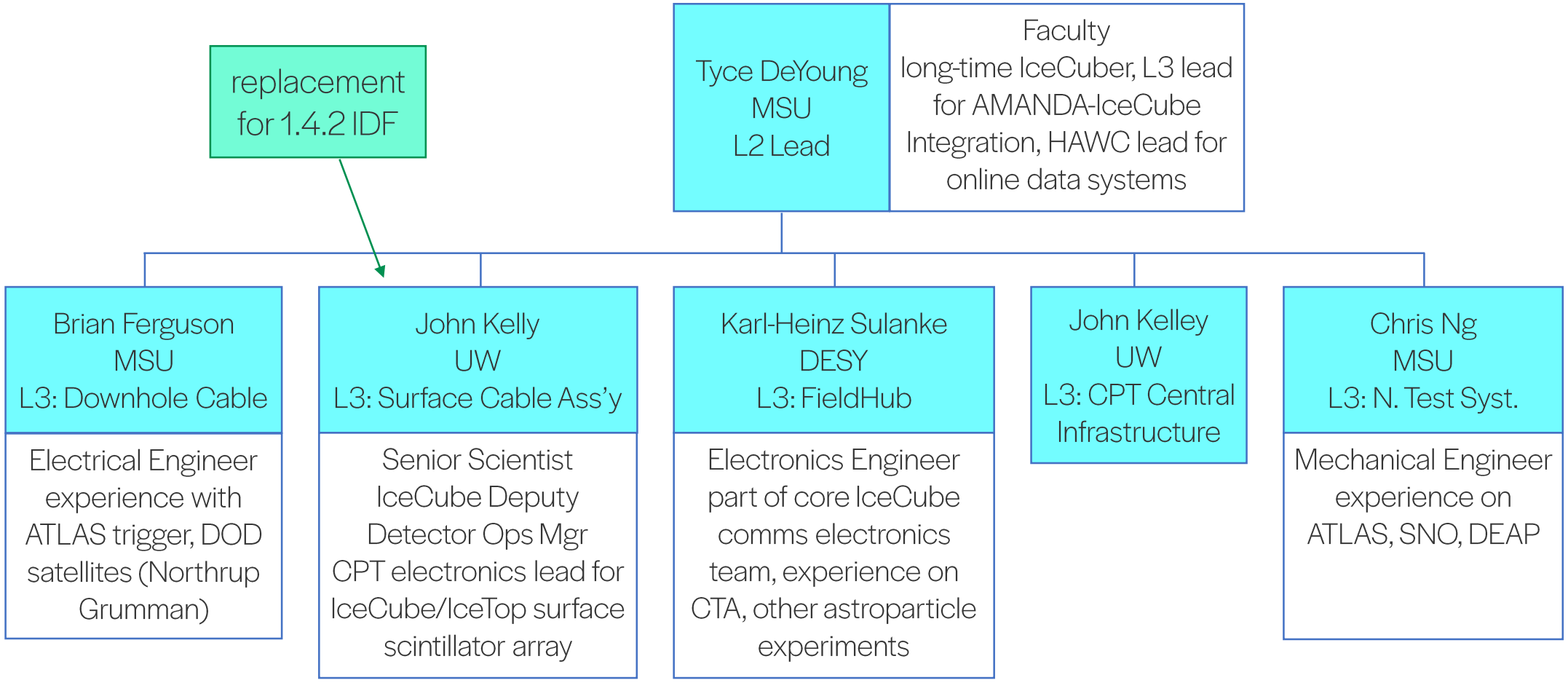
WBS 1.4 Scope

- The physical and electronic systems providing the interface between new sensor and calibration instrumentation and ICL/station infrastructure (power, communications for control and readout, global timing). Deliverables include the physical cables and structures to which new instruments are connected, the surface readout electronics, software, and firmware, and the systems for connecting these readout electronics to the station network and power system and the IceCube master clock. This category also includes construction of a test system in the Northern Hemisphere for testing DAQ and control software and firmware prior to deployment at Pole.
- Note: the surface readout electronics module (FieldHub) uses the Ice Comms Module to provide underlying communications and synchronization functionality for the in-ice devices. The ICM and its associated firmware are part of WBS 1.3 due to tight integration with the DOM electronics. After review, it was decided to move the FieldHub software systems to WBS 1.6. A CR updating the WBS Dictionary and clarifying this division of responsibility is in process.

WBS 1.4 Deliverables



WBS 1.4 Organization

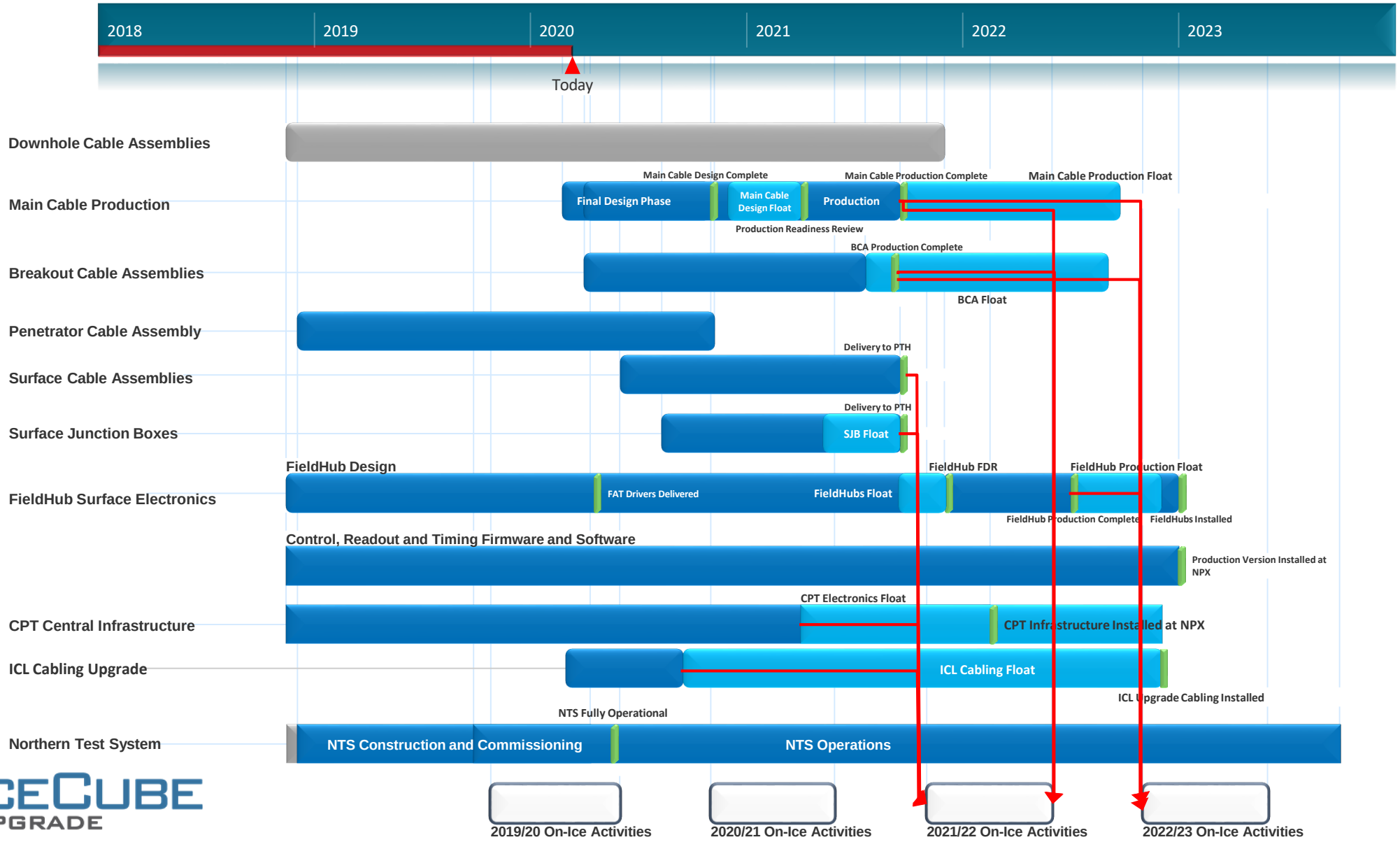


WBS 1.4 Key Requirements

no changes since last year

- Main cable bandwidth
  - 1.5 Mbps (8b10b) per wire pair (baseline comms bandwidth available with IceCube quads)
  - Verified with test quads, to be confirmed with first-article cable inspection
- Main cable crosstalk (soft requirement)
  - 50 dB min. NEXT, 30 dB min. ELFEXT from 100 kHz to 2.0 MHz (baseline specification from IceCube, affects bandwidth and RapCal timing)
  - Verified with test quads, to be confirmed first-article cable inspection
- Synchronization to IceCube Master Clock
  - 1 ns precision on global timing sync (required to be subdominant relative to RapCal DOM timing precision)
  - To be verified at NTS
- Integration with IceCube DAQ
  - Must operate under experiment control, global trigger, PnF data pipeline identically to IC
  - To be verified at NTS/SPTS
- FieldHub comms
  - Must communicate with/control all in-ice instruments (DOMs and calibration devices)
  - To be verified at DOM assembly sites, Northern Test System (NTS)

WBS 1.4 Schedule



WBS 1.4 – Milestones and Key Activities

WBS	Milestone or Activity	Scheduled Finish Date	Forecast Date (Actual if Finished)	Margin (Days)
1.4.1.1	Main Cable Design Complete	10/30/20	5/29/20	154
1.4.1.1	First Article Main Cable Delivered for Evaluation	2/1/21	10/30/20	94
1.4.1.1	*Main Cable Production Readiness Review	4/2/21	12/4/20	122
1.4.1.1	*Main Cable Production Complete	9/16/21	4/30/21	139
1.4.1.1	*Main Cable Shipping to PTH	9/30/21	5/14/21	139
1.4.1.2	Breakout Cable Assembly Design Review	2/1/21	1/4/21	28
1.4.1.2	Breakout Cable Assembly Production Complete	9/1/21	7/19/21	44
1.4.1.3	Penetrators Shipped to DOM Assembly Facilities	2/25/20	4/20/20	-56
1.4.2.1	*Surface Cable Assembly Delivery to PTH	9/16/21	5/31/21	108
1.4.2.2	*Surface Junction Box Delivery to PTH	9/16/21	5/31/21	108
1.4.2.3	ICL Upgrade Patch Cabling Installed	2/1/22	1/21/22	11
1.4.3.1	FAT Drivers Delivered	4/16/20	4/1/20	15
1.4.3.1	FieldHub Final Design Review	12/1/21	9/14/21	78
1.4.3.1	FieldHub Production Complete	7/1/22	4/1/22	91
1.4.4.2	Power Supply Final Design Review	8/2/21	4/2/21	122
1.4.5.4	Northern Test System Fully Operational	5/15/20	5/15/20	0

*Late finish directly delays project schedule

WBS 1.4 NSF Supported Cost Estimate to L3

1.4 Communication, Power and Timing	Project Year					
WBS L3	Year 1* Actuals	Year 2	Year 3	Year 4	Year 5	WBS Total
1.4.0 Management	**$26,100**	**$27,940**	**$25,670**	**$27,778**	**$25,536**	**$106,925**
Labor		$21,585	$19,983	$21,741	$22,167	$85,476
M & S		$775	$694	$736	$732	$2,937
Travel		$5,580	$4,994	$5,301	$2,637	$18,512
1.4.1 Downhole Cable Assembly	**$189,457**	**$461,528**	**$173,634**	**$6,037**	**$732**	**$641,931**
CapEx		$62,000	$0	$0	$0	$62,000
Labor		$281,418	$140,085	$0	$0	$421,503
M & S		$57,350	$6,243	$736	$732	$65,061
Travel		$60,760	$27,306	$5,301	$0	$93,367
1.4.2 Surface Cables	**$6,510**	**$31,825**	**$343,013**	**$727**	**$0**	**$375,565**
CapEx		$0	$286,400	$0	$0	$286,400
Labor		$29,510	$40,597	$0	$0	$70,107
M & S		$2,315	$11,022	$727	$0	$14,064
Travel		$0	$4,994	$0	$0	$4,994
1.4.4 CPT Central Infrastructure	**$26,708**	**$97,421**	**$46,385**	**$11,649**	**$0**	**$155,455**
CapEx		$12,484	$14,947	$0	$0	$27,431
Labor		$78,664	$27,841	$9,178	$0	$115,683
M & S		$765	$1,132	$727	$0	$2,624
Travel		$5,508	$2,465	$1,744	$0	$9,717
1.4.5 Northern Test Systems	**$29,234**	**$39,525**	**$694**	**$736**	**$732**	**$41,687**
Labor		$31,620	$0	$0	$0	$31,620
M & S		$7,905	$694	$736	$732	$10,067
Annual Total	**$278,009**	**$658,239**	**$589,396**	**$46,927**	**$27,001**	**$1,321,563**

* - Year 1 is presented for informational purposes only

WBS Contributions in Kind

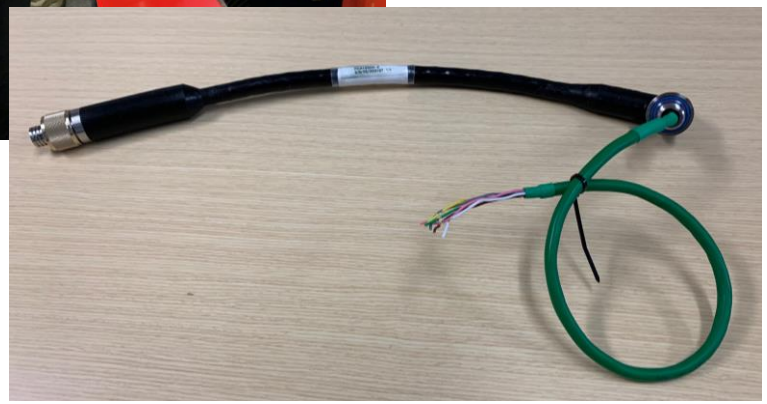
WBS	Contribution
1.4.1 Downhole Cable Assembly	Production main cables (MSU) Penetrator cable assemblies for DEgg production (Chiba) Penetrator cable assemblies for mDOM production (DESY)
1.4.3 FieldHub	FieldHub electronics design (DESY) FieldHub production (DESY) FieldHub firmware (DESY) FieldHub control software (UW) - moving to 1.6.1 via CR
1.4.5 Northern Test System	NTS facility (MSU)

WBS 1.4 Risks and Mitigation

- Main cable electrical performance may be worse than anticipated
  - Working with Hexatronic and partners to develop option based on Gen1-type twisted quads – nearly complete
  - Otherwise, additional comms firmware engineering effort required to accommodate higher levels of noise or cross talk
- Main cable production delays
  - Aggressively pushing schedule for first-article main cable production by fall/winter 2020
  - Main cable production deadline of Sept 2021 based on pre-staging two cables on ice over winter
- ICM (DOM/FieldHub) firmware delays impacting DOM production schedule
  - Scope clarified w.r.t. WBS 1.3, 1.6, and Ops, additional FTEs committed

WBS 1.4 Technical Progress

- Penetrator cable assembly prototypes tested to 700 bar by manufacturer and in DEggs
- Production now underway with minor design tweaks
  - Some coronavirus-related delays but delivery anticipated before planned DEgg assembly date



WBS 1.4 Technical Progress

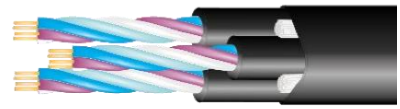
- New main cable design from Hexatronic based on triplets of Gen1-type twisted quads
  - Final assembly by partner company (possibly combined with breakout connector installation) – discussions moving forward productively
  - Short prototype cable in production, pull test planned in coming weeks

Surface to DOM cable TEH 301 9110

Cable design

- *Conductor*	solid bare copper wire Ø 0.9mm
- *Insulation*	Solid PE
- *Pair*	Quad - 2 pair
- *Quad jacket*	PE-LLD (Quad number marked Q1 to Q21)
- *Sub unit*	3x Quad
- *Water blocking*	Water swellable yarn
- *Sub unit jacket*	PE-LLD (marked Quad 01-03, 04-06,.. ie)
- *Lay up*	7 subunits concentric stranded
- *Strength member*	5x bundles aramid yarn (each 6x8050 dtex)
- *Water blocking*	PIB filling compound
- *Auxiliary pairs*	1 Quad unjacketed,1 signal pair
- *Jacket*	PE-LLD
- *Screen*	Copper tape thickness =0.1 mm 2 tapes 0,1x45mm spiral 25% overlap
- *Drain wire*	Tinned stranded copper wire 2x 20 AWG (0.5mm²)
- *Strength members*	30 bundles aramid yarn 8050 dtex spiral in two opposite layers
- *Jacket*	TPE-U compound.

Subunit 3x Quad
Jacketed cable

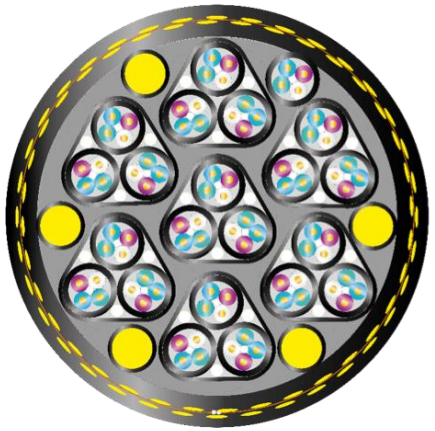


General data

Operating temp	–55 to +80 °C
Handling temp	–40 to +80 °C
Storage temp	–80 to +80 °C
Operating pressure	1 to 250 bar
Over pressure	450 bar
Color	Black
Cable diameter	nom 51 mm
	max 2.3 kg/m
ce	
h member	min 25 kN
h member	min 25 kN
t break	
mber	max 2.5 %
tic bend radius complete cable 400 mm	
tic bend radius individual quad 80 mm	

data

sistance	min 5000 Mohm
	nom 100 nF
t 1 MHz	145 ±10 ohm
at 1 MHz	max 20 dB
osstalk at 2 MHz	min 50 dB
al Level	
2 MHz	min 30 dB
oltage	max 400 V DC
oltage	max 280 V AC
urrent	max 200 mA DC
urrent	max 140 mA AC



WBS 1.4 Technical Progress

- Evaluation of bandwidth requirements and data budget:
  - DOM Comms Bandwidth Worksheet

    (https://uwprod.sharepoint.com/:x:/r/sites/icecubeupgrade/_layouts/15/Doc.aspx?sourcedoc=%7BE94F091E-230E-4DC3-9943-6B003C6D0433%7D&file=DOM%20Comms%20Bandwidth%20Worksheet.xlsx&action=default&mobileredirect=true)
- Performance demonstrated on evaluation triplet – no observable crosstalk, 2 Mbit performance demonstrated w/ no errors observed in 720 MB of transmitted data
- Currently predict 27% bandwidth margin on busiest pairs (much more on typical pairs)
  - Increase to 3 Mbit appears feasible, if needed, without extensive work

Maximum-rate pair bandwidth

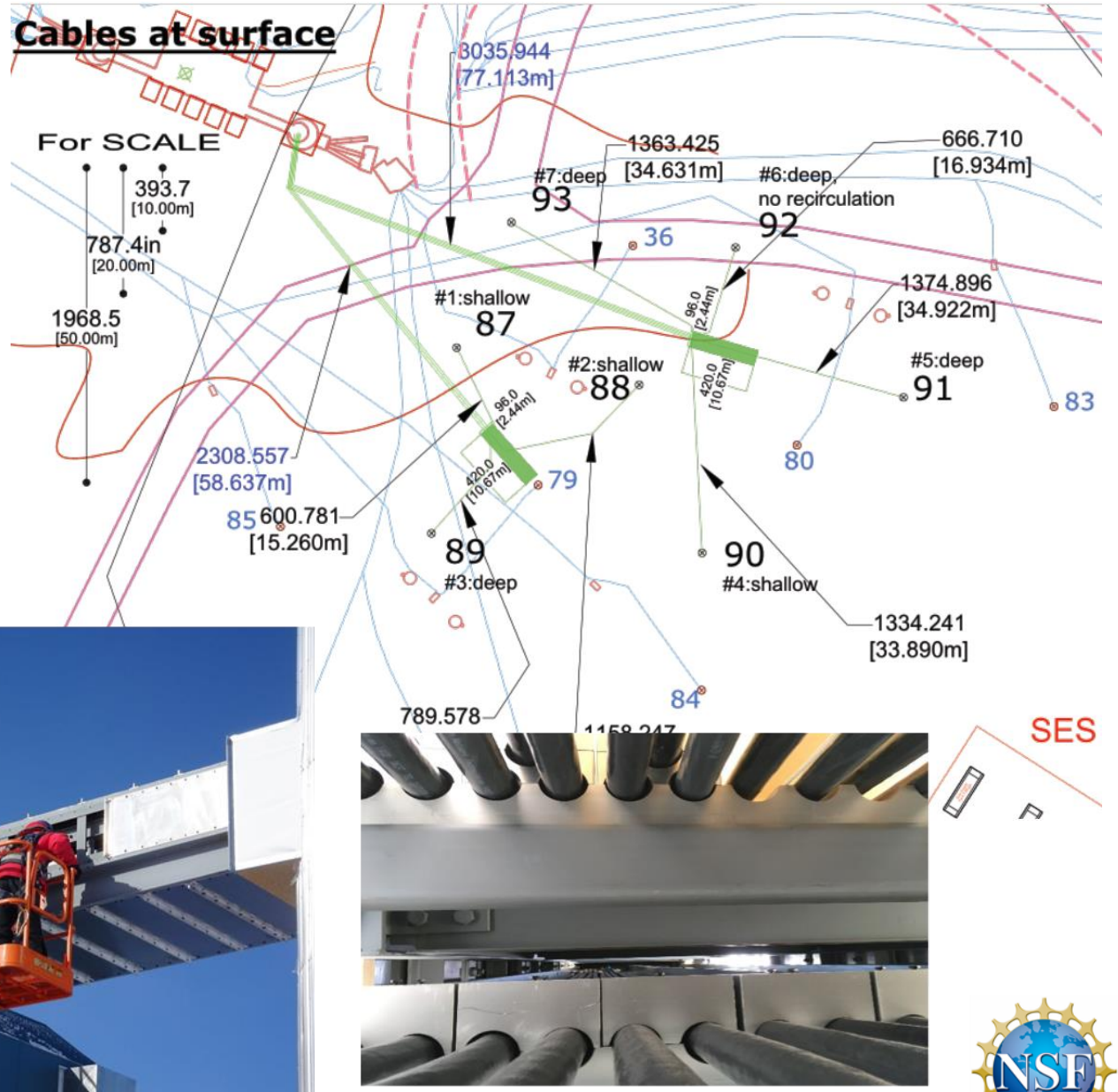
Net data bandwidth	1,552	kb/s		
mDOM data rate	529.8	kb/s		
DEgg data rate	157.5	kb/s		
Total data rate	1,217	kb/s		Highest data rate is for pairs with 2 mDOMs plus one DEgg

WBS 1.4 Technical Progress

- IDF replaced by surface cables and junction boxes (installation 21/22)
- Design and installation plan being finalized based on 19/20 recon w/ ASC
- Plan to procure surface cables from Hexatronic following Gen1 design

Cables in tower

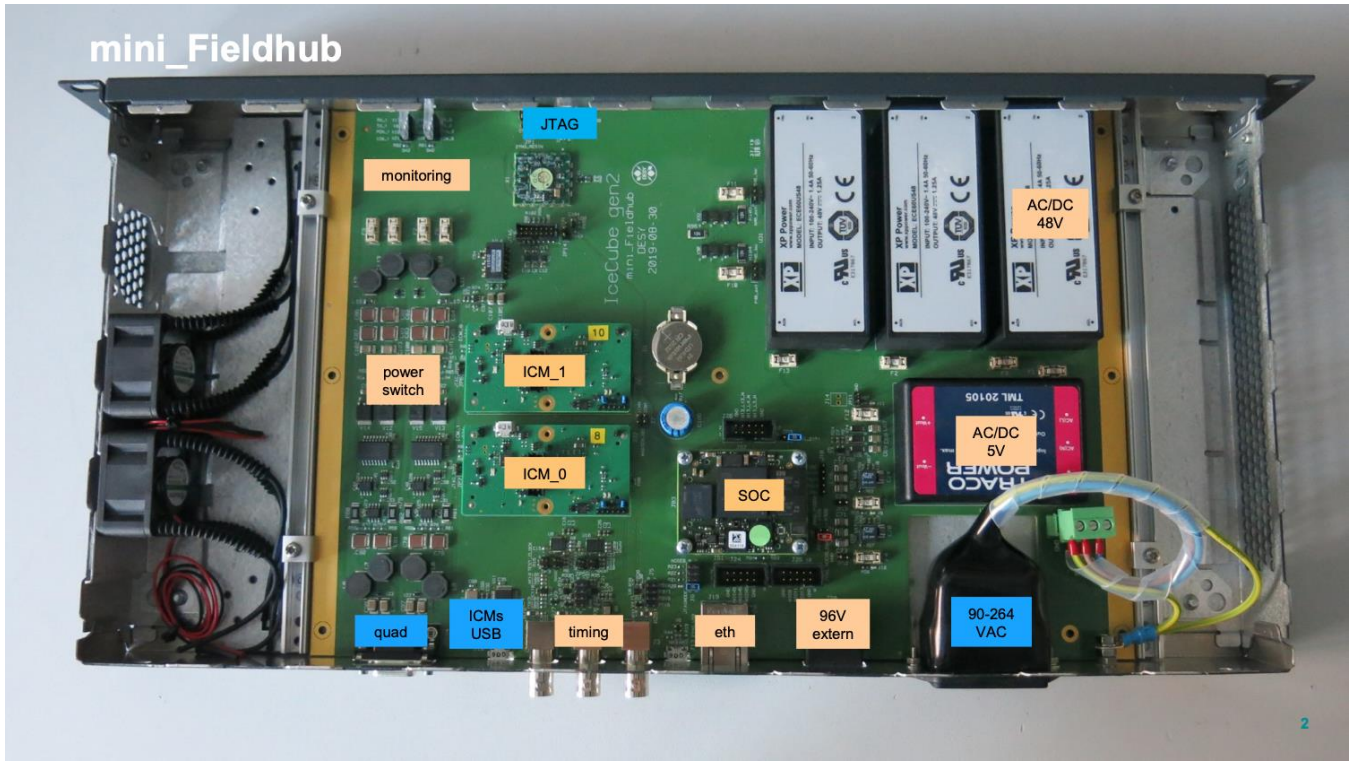
Accessing side panels



Cables entering the ICL

WBS 1.4 Technical Progress

- First surface readout electronics modules (“mini-FieldHubs”) produced
  - Distributed to DOM production sites and firmware developers
- ICM-related firmware development lags behind aggressive DOM production schedule
  - No current impact on overall project schedule
  - Detailed replanning just completed with clarification of responsibilities betw. 1.3, 1.4, 1.6 and additional resources brought to bear (CR in process)



WBS 1.4 Previous and Future Reviews

• 08 / 2019	Penetrator cable assembly PDR	
• 12 / 2019	Penetrator cable assembly FDR/PRR	report
• spring 2020	Main cable PDR	
• late spring 2020	Power supply and distribution PDR	
• summer 2020	Main cable FDR	
• fall 2020	Timing infrastructure FDR	
• fall 2020	FieldHub PDR	
• fall 2020	Surface cable and junction box FDR	
• winter 2020	Breakout cable PDR	
• Nov/Dec 2020	Main cable PRR	
• spring 2021	Breakout cable FDR	
• spring 2021	Power supply and distribution FDR	
• winter 2021	FieldHub FDR	

WBS 1.4 Remaining Issues and Challenges

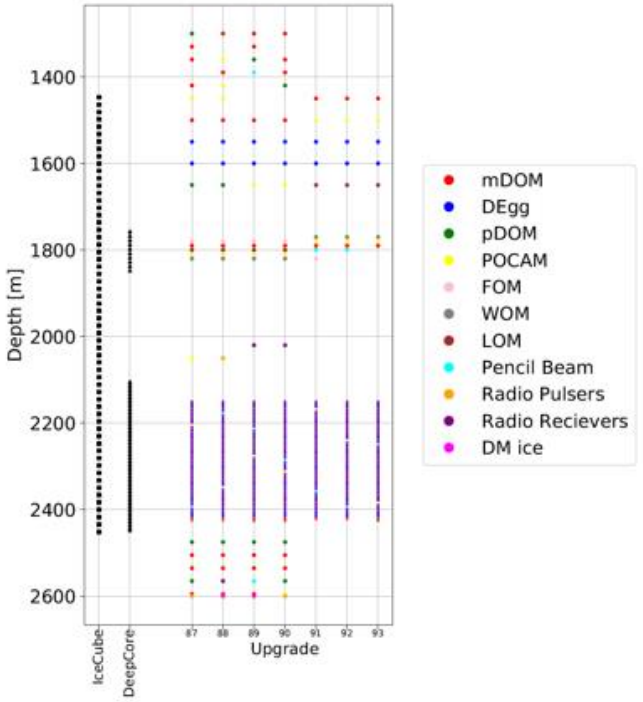
- New Hexatronic main cable design
  - Mechanical validation of cable next month, then finalize breakout connector design and procurement
  - First-article production in fall/winter 2020, remaining strings in 2021 – six months of schedule float but delays would have major impact
- Rapid design/review schedule for surface cables and junction boxes
  - ICL cable tower reconnaissance completed in 19/20, no issues identified – awaiting GPR confirmation of cable routing plan
- ICM/FieldHub comms firmware development is lagging
  - Scope at the boundary of 1.3, 1.4 and 1.6 – distributed efforts
  - Detailed replanning will accelerate progress

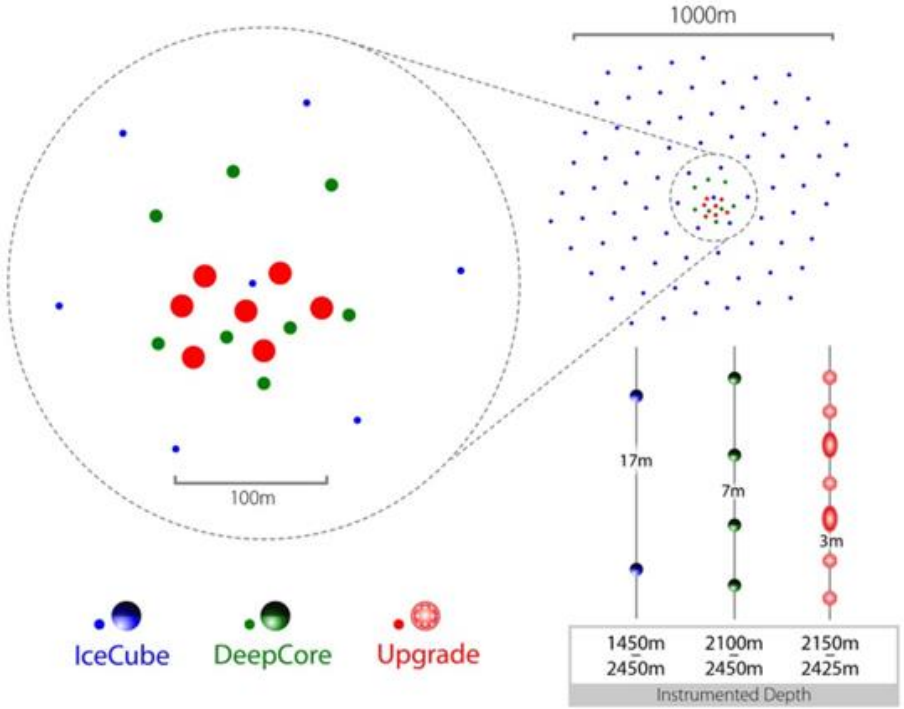
WBS 1.4 Summary

- Shift away from SPOT provided important schedule margin for main cable development
  - New design from Hexatronic under evaluation: electrical tests excellent, mechanical test this spring
  - On track for RFP and contract in late spring / early summer
- Penetrator cables in production, SCA and BCA design beginning
- FieldHub hardware on track, firmware development plan clarified
  - Low-level hardware tests of ICM and cable indicate sufficient bandwidth available based on DOM performance measurements
- CPT power, timing infrastructure development proceeding well
- NTS ready to begin operations as components are delivered
  - DAQ servers installed on private network connection to SPTS
  - GPS clock installed, mini-FieldHub en route from DESY, Hexatronic quad available
  - Dark boxes under construction for first DOMs (DEggs) to arrive

Backup

Upgrade Scope:



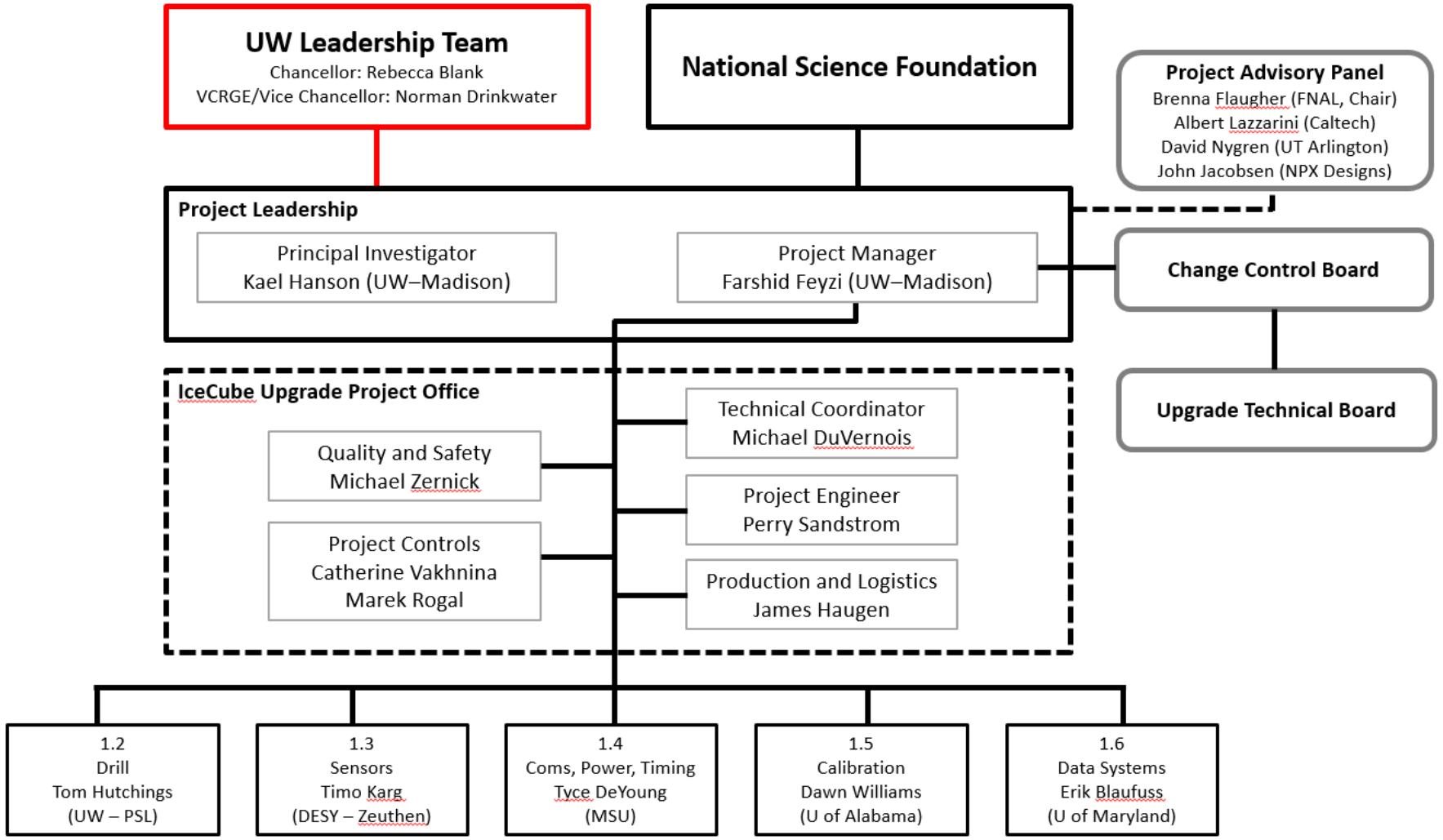


String	87	88	89	90	91	92	93	TOTAL
mDOM	55	56	58	53	61	59	60	**402**
DEgg	39	39	40	39	40	40	40	**277**
pDOM	1	1	2	1	2	4	3	**14**
WOM	2	2	1	2	1	1	1	**10**
FOM	2	2	0	0	1	1	1	**7**
POCAM	2	2	5	3	2	3	4	**21**
PB	1	2	1	2	3	1	1	**11**
PS	1	1	1	1	1	1	1	**7**
DM ice	0	0	1	0	0	1	0	**2**
RP	0	1	0	0	1	0	1	**3**
RR	1	0	0	0	0	2	0	**3**
AH	0	0	1	1	0	0	0	**2**
LOM	2	1	1	3	0	1	1	**9**
AP	2	1	2	1	1	1	2	**10**
ALL	**108**	**108**	**113**	**106**	**113**	**115**	**115**	**778**

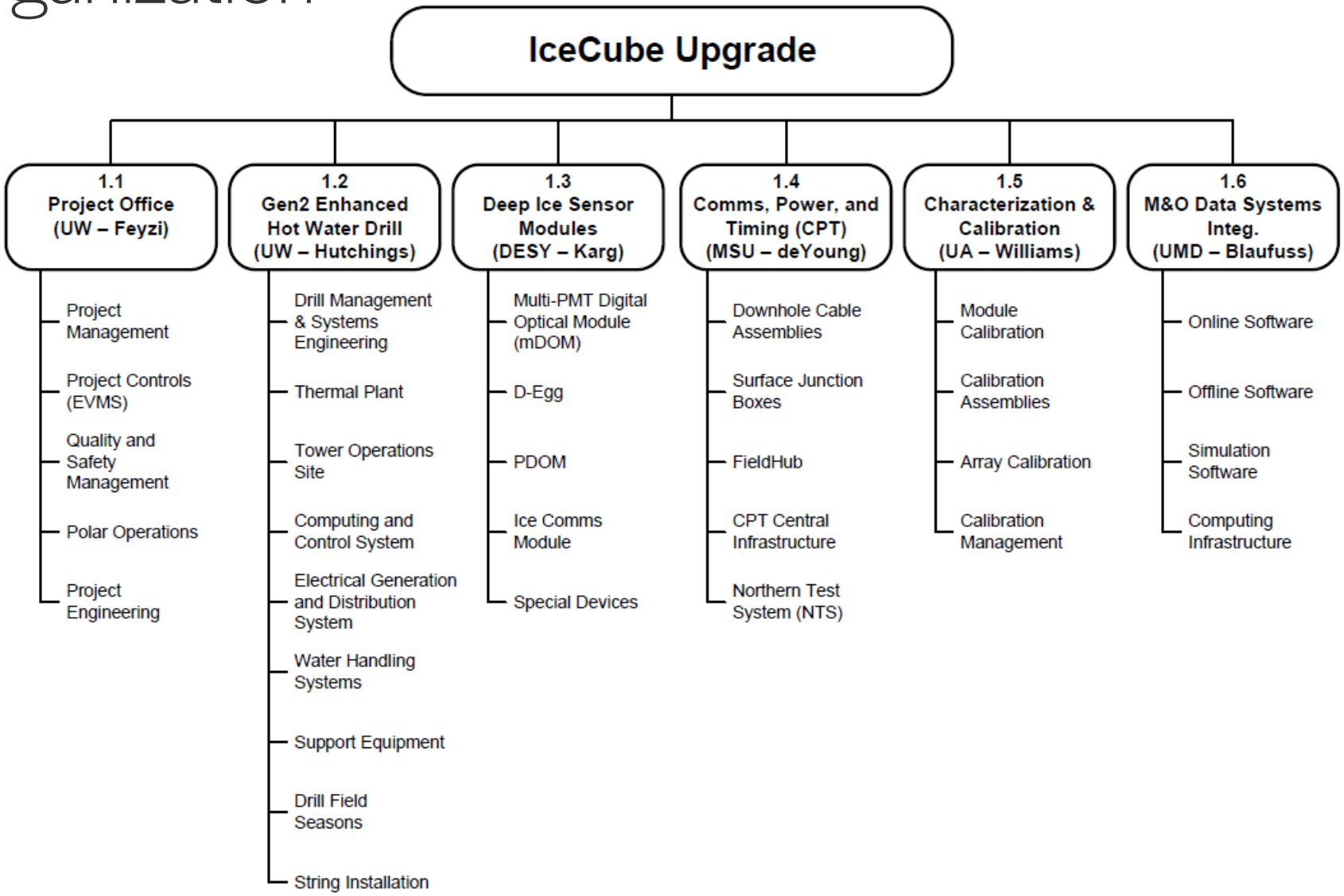
Upgrade Objectives:

1. Neutrino Properties
2. Recalibration and Reanalysis of IceCube Data
3. IceCube-Gen2 Research and Development (not directly funded)

Project Office and Level 2 Organization

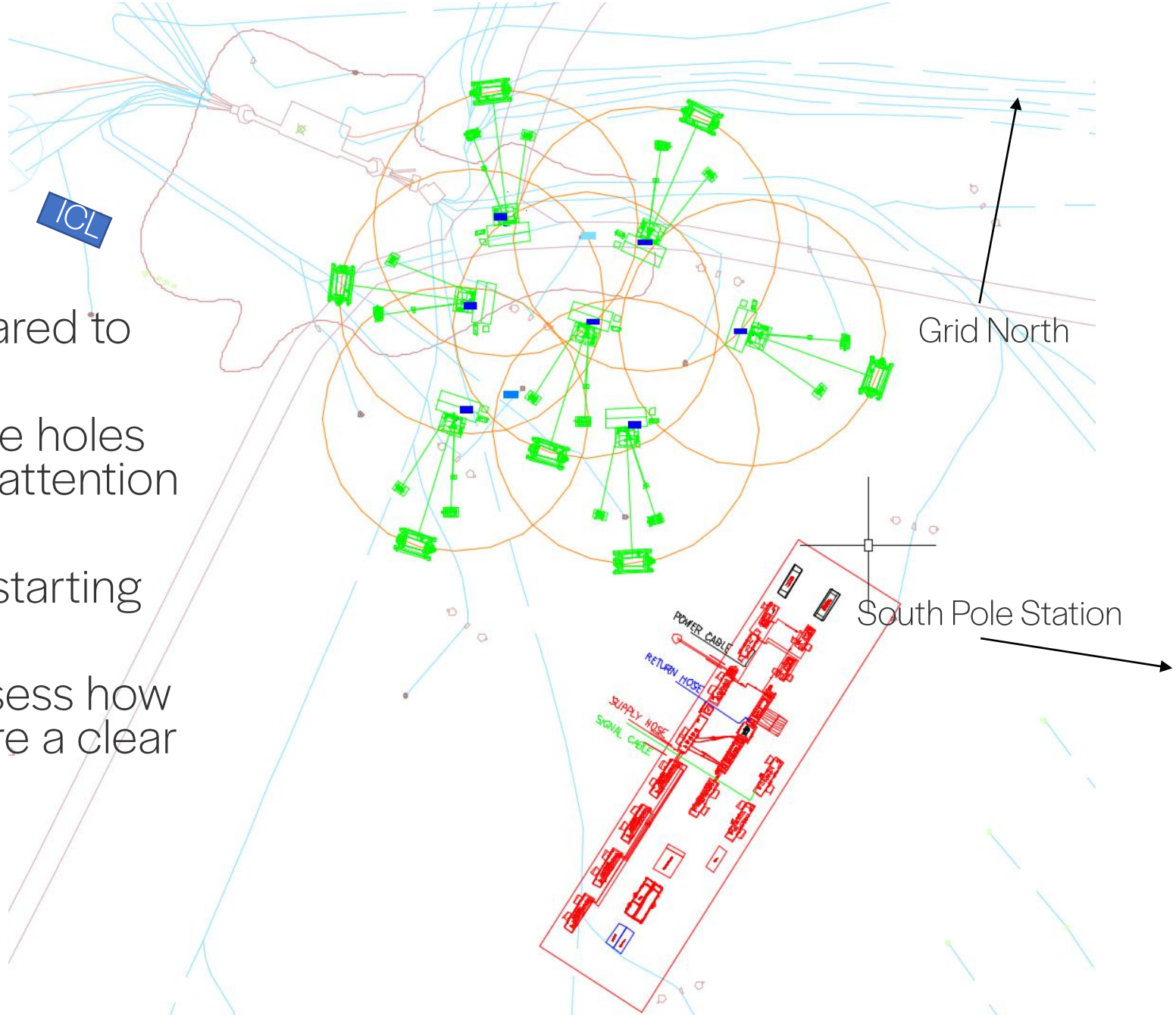


Level 3 Organization



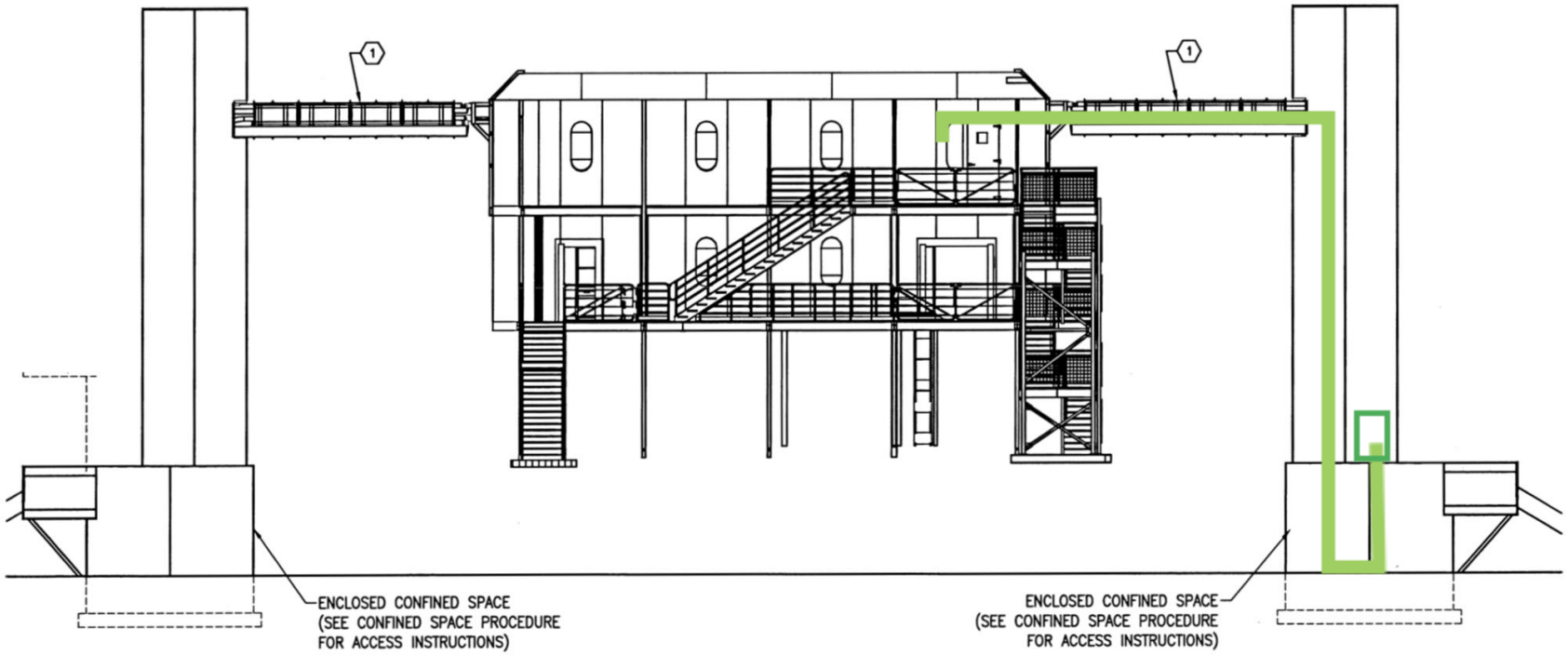
Surface Plan

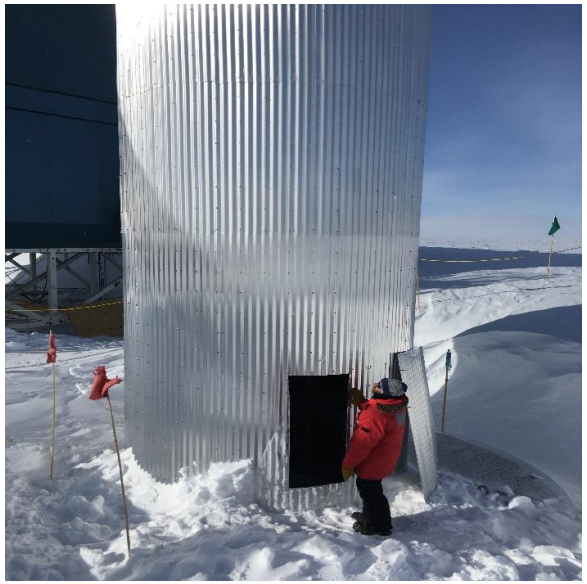
- Very close holes compared to IceCube Gen1
- Integration with IceCube holes and cables need close attention
- Logistics and cable management planning starting this year
- Integration with ICL, assess how we could do this. Is there a clear path



Surface Cable Route into ICL

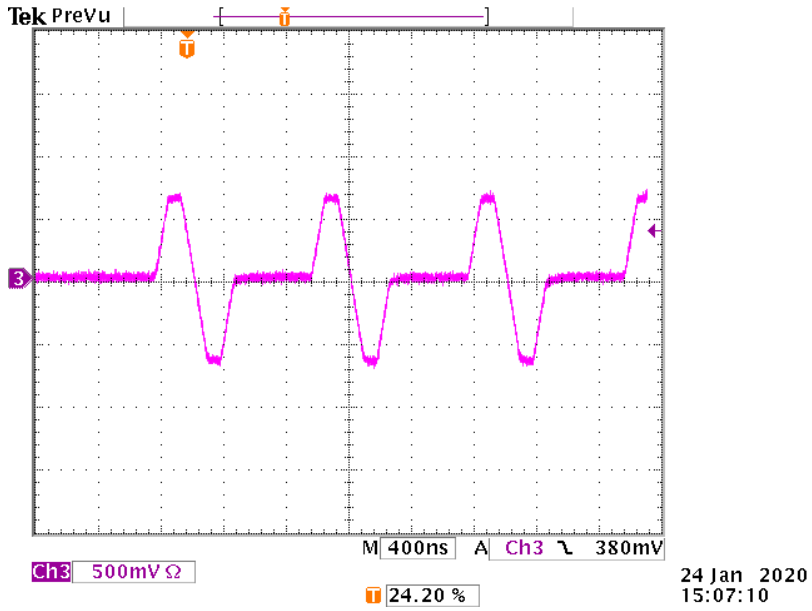
- Tower modifications planned for 20–21 season, detailed discussion of plans with ASC on March 5





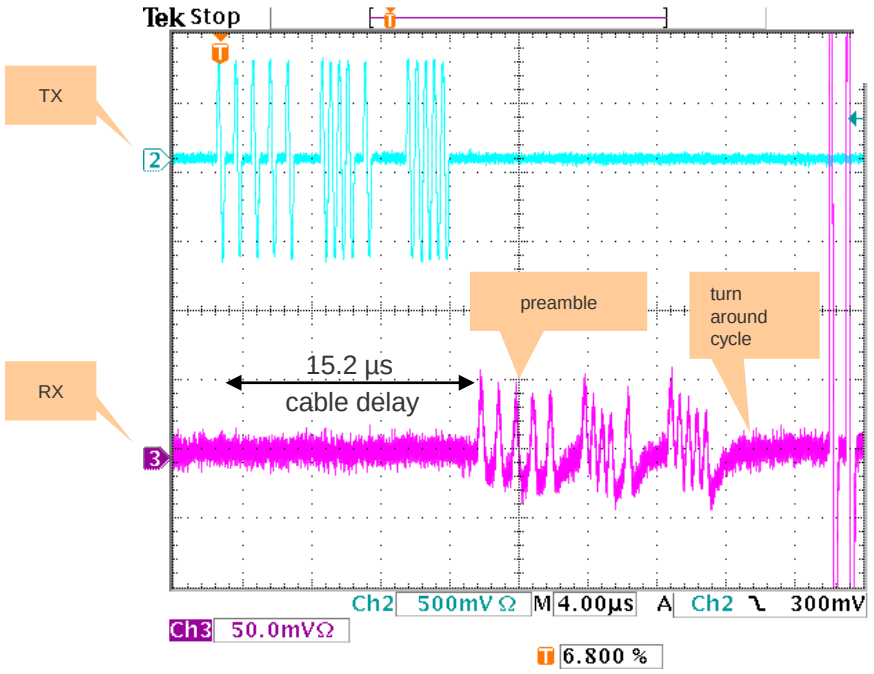
ICM / mini-FieldHub Comms Status

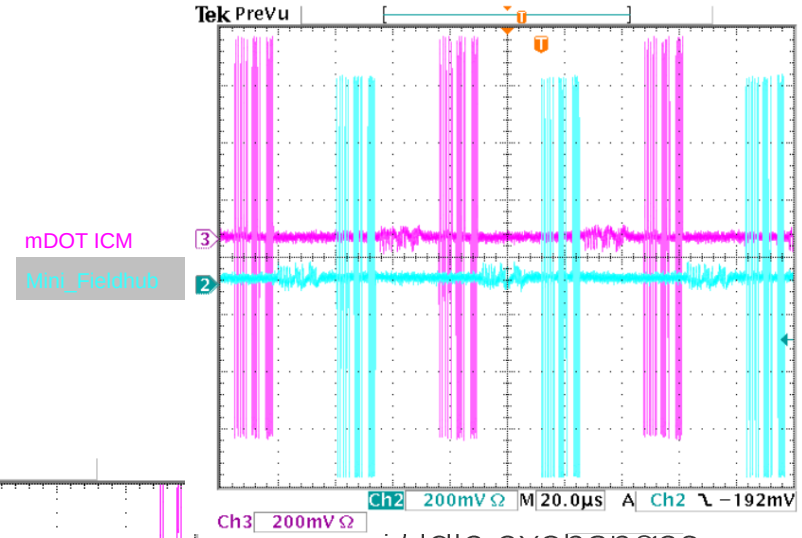
- Firmware Rev. 019
- 2MBd data rate
- Data bytes on the wire are 8b10b encoded (different to gen1)
- Data bits are ASK encoded (‘1‘ = bipolar pulse, ‘0‘ = quiet line)
  - AFE-friendly trapezoidal waveform, e.g. 001010101 sequence
- Point to point connection, mini_Fieldhub buffer <-> xDOM buffer
- Transparent replacement of the local xDOM USB connection by the mini_Fieldhub USB demonstrated successfully
- Full hardware flow control between the mini_Fieldhub and the MCU
- No communications parameter adjustment required (different to gen1)
  - Works with cable lengths between 1m to 3000m



ICM / mini-FieldHub Comms Status

- Current packet format is point-to-point (no addressing, packet size info, etc....)
  - Half-duplex, ICMs exchange idle tokens
  - No retransmission, mini-FH re-initiates communication after 40 µs timeout
- Planned final data format has 1-3% packet overhead (dep. on packet size)





3 Idle exchanges

Tx through 2800 m of Hexatronic triplet

Final Comms Format (Preliminary)

Control Packet Format – used as acknowledge, data read request, DOM power enable, etc.

	8b10b code	# of bytes	remark
Preamble	D21.5	1	B“1010101010“ for baseline flattening and decoder teach-in
Start of Frame	K28.0	1	more robust than a single start bit (gen1)
DOM address &_sequence		1	DOM address and sequence number, used for retransmits
Function Code		1	Up to 256 functions
CRC_32		4	
End of Frame	K28.7	1	Unique pattern in a 8b10b encoded data stream

Data Packet Format

	8b10b code	# of bytes	remark
Preamble	D21.5	1	B“1010101010“ for baseline flattening and decoder teach-in
Start of Frame	K28.0	1	Comma operator, more robust than a single start bit (gen1)
DOM address &_sequence nr.		1	DOM address and sequence number, used for retransmits
Packet Length		2	1…2048, 16bit words always
Data Bytes	Dxx.y	2 to 4096	2 to 4096 bytes
CRC_32		4	Like Gen1
End of Frame	K28.7	1	Unique pattern in a 8b10b encoded data stream

Maximum-rate pair bandwidth

Raw bit rate	2.0	Mbps		
Byte transmission time	5.0	µs		8b10b encoding, 10 bits transmitted per byte
Planned data packet format				
Preamble	1	bytes		B“1010101010“ for baseline flattening and decoder teach-in
Start of frame	1	bytes		Comma operator, more robust than a single start bit (gen1)
DOM address & sequence	1	bytes		DOM address and sequence number, used for retransmits
Packet length	2	bytes		1…2048, 16 bit words always
Data bytes	4096	bytes		from 2 to 4096 bytes per packet
CRC_32	4	bytes		as in gen1
End of frame	1	bytes		Unique pattern in a 8b10b encoded data stream
Total data packet size	4106	bytes		
Communications overhead				Calculated for maximum packet size (i.e. minimum overhead)
Packet + frame transmit time	20,530	µs		
Cable delay	16	µs		
Turnaround cycle	4	µs		quiet time between Rx and Tx
Acknowledgement packet	45	µs		9 bytes
Total time per packet	20,615	µs		
Net data bandwidth	1,552	kb/s		
mDOM data rate	529.8	kb/s		
DEgg data rate	157.5	kb/s		
Total data rate	1217	kb/s		Highest data rate is for pairs with 2 mDOMs plus one DEgg

mDOM Data Rate Estimator

Base Data				
Dark rate per PMT	500	s-1		enter the dark rate per PMT in your module
Frequency of DOM clock	40	MHz		local clock in DOM
Full time stamp	48	bit		Assume we will use an 81-day clock rollover for byte-aligned timestamps (as Gen1)
Delta t between full time stamps	1.0E+06	ns		change this value until the data rate is minimal
SPE pulse time resolution	0.7	ns		enter time resolution of pulse templates used for unfolding - same as Gen1
Number of PMTs	24			enter the number of PMTs in your module
Group Header				group defined by consecutive sampling bins with amp. > threshold (0.25 pe)
DOM # on wire pair	0	bit		not needed as probably each module has its own channel
PMT #	5	bit		automatically calculated
Delta t relative to full time stamp	21	bit		automatically calculated
Feature extraction	1	bit		0 = not feature extracted; 1 = feature extracted
Complex Pulse Sampling				
Samples for baseline	3			samples prior to waveform start for baseline determination
Waveform sampling rate	100	MSPS		
Waveform length	200	ns		average length of a complex waveform
Amplitude resolution	12	bit		resolution of ADC
Feature extraction				
Amplitude resolution	12	bit		enter resolution of feature-extracted amplitude
Data Rates per DOM				
Complex waveform rate	2	s-1		Rate of complex multi-PE waveforms per PMT
Complex waveform size	303	bit		
Waveform data rate per PMT	0.59	kb/s		
Waveform data rate for all PMTs	14.2	kb/s		
Extracted SPE size	39	bit		Assuming pulses which look like scaled SPE templates will be extracted in FPGA
Byte-aligned SPE size	40	bit		Assume we will avoid bit-packing, so SPE data will use whole bytes
SPE data rate per PMT	19.5	kb/s		
SPE date rate for all PMTs	468.8	kb/s		
Absolute time stamp data rate	46.9	kb/s		
Total data rate per module	529.8	kb/s		this is the required data bandwidth per module after feature extraction assuming that ALL pulses are (scaled) single PE pulses (distribution of amplitudes needs to be checked in measurements)

DEgg Data Rate Estimator

Base Data				
Dark rate per PMT	1300	s-1		enter the dark rate per PMT in your module
Frequency of DOM clock	40	MHz		local clock in DOM
Full time stamp	48	bit		Assume we will use an 81-day clock rollover for byte-aligned timestamps (as Gen1)
Delta t between full time stamps	1.0E+06	ns		change this value until the data rate is minimal
SPE pulse time resolution	0.7	ns		enter time resolution of pulse templates used for unfolding - same as Gen1
Number of PMTs	2			enter the number of PMTs in your module
Group Header				group defined by consecutive sampling bins with amp. > threshold (0.25 pe)
DOM # on wire pair	0	bit		not needed as probably each module has its own channel
PMT #	1	bit		automatically calculated
Delta t relative to full time stamp	21	bit		automatically calculated
Feature extraction	1	bit		0 = not feature extracted; 1 = feature extracted
Complex Pulse Sampling				
Samples for baseline	3			samples prior to waveform start for baseline determination
Waveform sampling rate	240	MSPS		
Waveform length	300	ns		average length of a complex waveform
Amplitude resolution	12	bit		resolution of ADC
Feature extraction				
Amplitude resolution	12	bit		enter resolution of feature-extracted amplitude
Data Rates per DOM				
Complex waveform rate	5	s-1		Rate of complex multi-PE waveforms per PMT
Complex waveform size	923	bit		
Waveform data rate per PMT	4.5	kb/s		
Waveform data rate for all PMTs	9.0	kb/s		
Extracted SPE size	35	bit		Assuming pulses which look like scaled SPE templates will be extracted in FPGA
Byte-aligned SPE size	40	bit		Assume we will avoid bit-packing, so SPE data will use whole bytes
SPE data rate per PMT	50.8	kb/s		
SPE date rate for all PMTs	101.6	kb/s		
Absolute time stamp data rate	46.9	kb/s		
Total data rate per module	157.5	kb/s		this is the required data bandwidth per module after feature extraction assuming that ALL pulses are (scaled) single PE pulses (distribution of amplitudes needs to be checked in measurements)