Effect of upgrades on the reliability of the Autosub AUV

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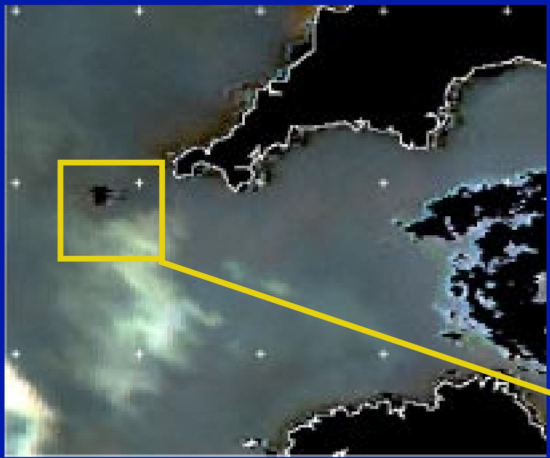
Outline

- The requirements and challenges of the 3-campaign Autosub Under Ice (AUI) programme
- Upgrades of software & hardware for AUI
- Results from two engineering trials cruises (2002)
  - Problems encountered, solved, identified, remaining
  - Successful mission segments
- Critical Items List - prioritise tackling the remaining problems
- Performance on the first AUI campaign (2003)
- What further work is needed to re-establish reliability?

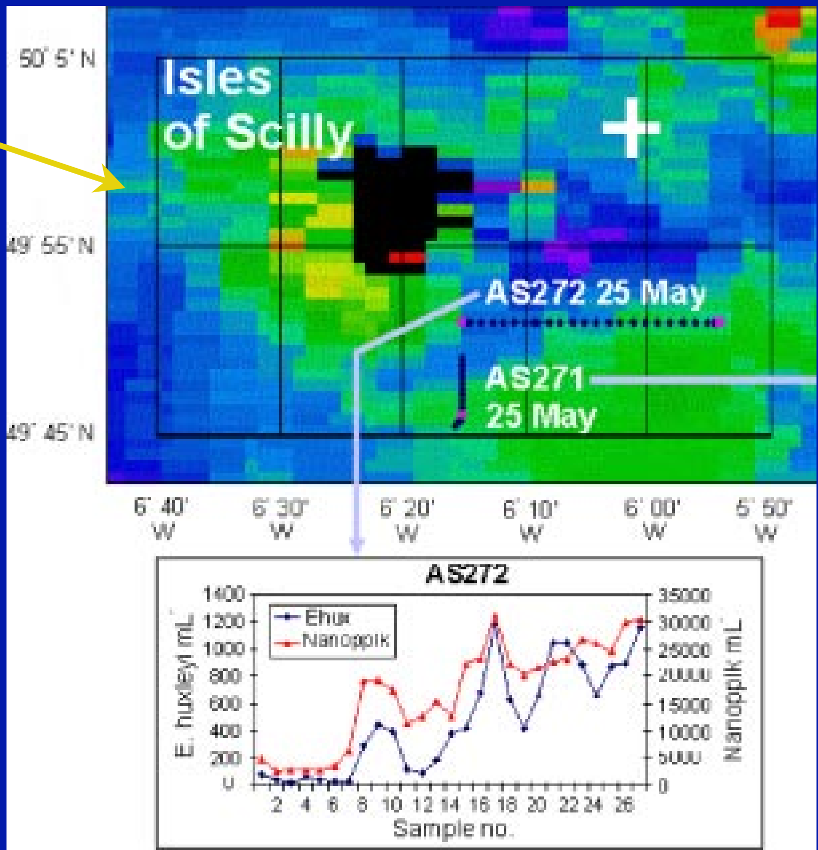
Last post-upgrade campaign- Scilly Isles, May 2001

Successful culmination of 121 missions within the 2-year Autosub Science Missions programme in UK waters, the Mediterranean Sea and the Weddell Sea, Antarctica.



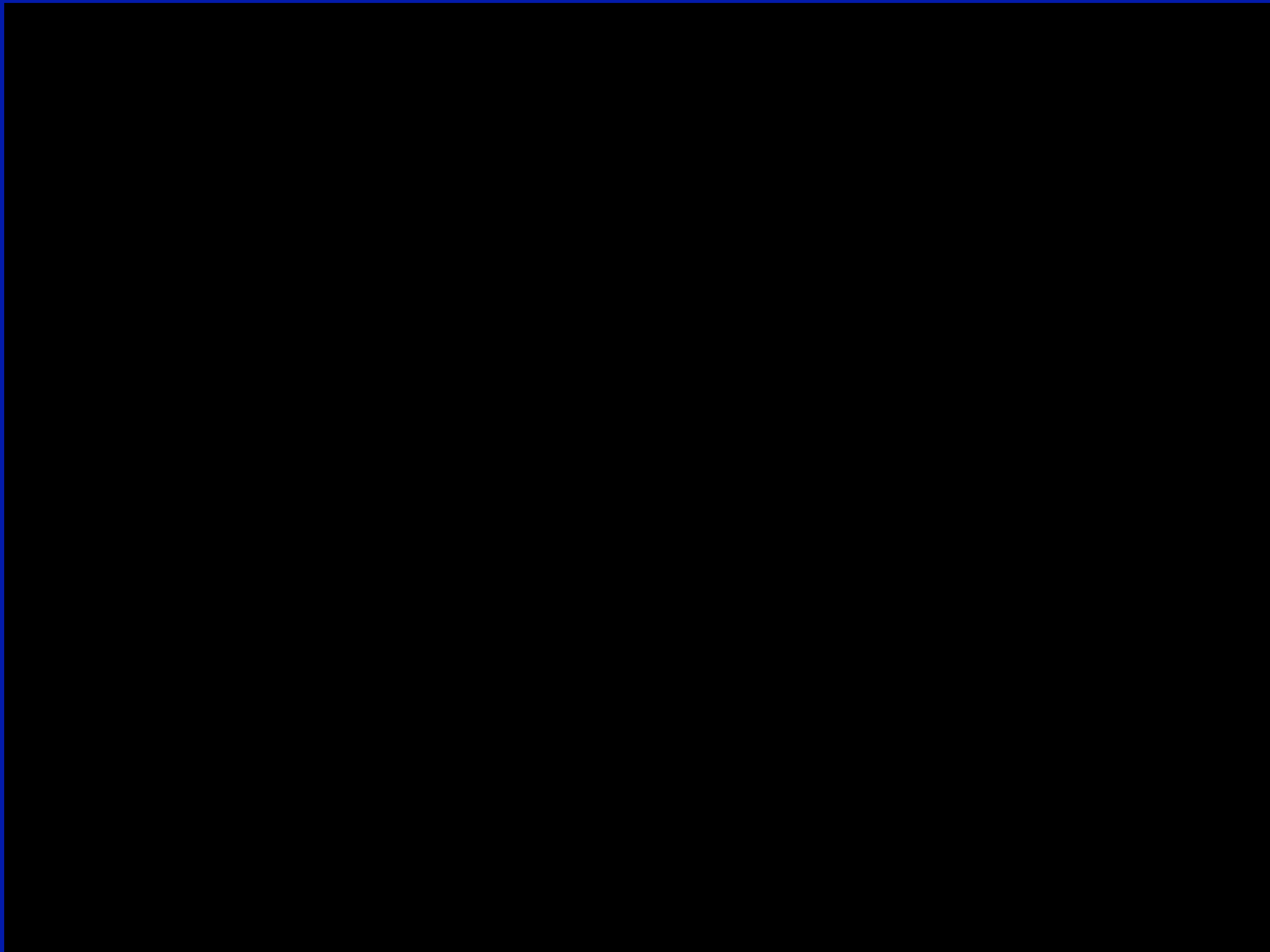
Seawifs satellite image, SW of UK, May 2001

Autosub deployment within Coccolithophore bloom



Comparison of satellite derived chlorophyll with cell counts and species identification by flow cytometer within Autosub

The (virtual) AUI mission post-upgrades: March 2003



Autosub Under Ice projects

- Controls on marine benthic biodiversity and standing stock in ice covered environments. *P A Tyler et al, Southampton*.
- Marine geological processes and sediments beneath floating ice shelves in Greenland and Antarctica: investigations using the Autosub AUV. *J Dowdeswell, Cambridge*.
- Sea ice thickness distribution in the Bellingshausen Sea. *M Brandon, Open University.*
- Observations and modelling of coastal polynya and sea ice processes in the Arctic and Antarctic. *P Wadhams et al., SAMS.*
- Autosub investigation of ice sheet boundary conditions beneath Pine Island Glacier. *D Vaughan, BAS.*
- Oceanographic conditions and processes beneath Ronne Ice Shelf. *K Nicholls, BAS.*
- Evolution and impact of Circumpolar Deep Water on the Antarctic continental shelf. *A Jenkins, BAS*.
- ISOTOPE: Ice Shelf Oceanography: Transports, Oxygen-18 and Physical Exchanges. *K Heywood, UEA.*

The Upgrade programme: Software

- Complete redesign of mission control software:
- Mission instruction format: the Opcode-Operand format was extended to allow 950 mission instructions per mission.
- Logical or of up to 3 events implemented (up from 1); ordered sequences of events to trigger next mission element added.
- Total number of mission events increased to 34 (from 7) - including two from payload equipment.
- Two conditionally entered mission termination scripts added.
- Scripted control output to payload equipment.
- Control mode for the vehicle's homing behaviour added.
- Mission compiler modified and new downloader developed as consequence of mission control redesign.
- Improve collision avoidance; in particular implement a more robust iceberg avoidance procedure.
- Add a special collision avoidance response: respond to minimum headroom (ice shelf above), minimum separation of ice shelf and seabed (grounding line).
- Provide for synchronisation of acoustic instruments.
- Remote control via acoustic link of sub-bottom profiler and mission initiation.

The Upgrade programme: Hardware

- 200 kHz swath bathymetric sonar for seabed mapping and swath observations of the underside of sea and shelf ice.
- 4 - 12 kHz chirp sub-bottom profiler to obtain the stratigraphy within sediments
- Water sampler capable of capturing up to 50 water samples, each of 250 ml, for later chemical analysis.
- 150 kHz acoustic Doppler velocity log and current profiler, needed to provide a bottom-track range of ~400 m.
  300 kHz instrument used in up-ward-looking mode.
- Inertial navigation system (INS) of 3 fiber-optic gyrocompasses, 3 accelerometers and processing firmware (Kalman filter). Replaced 3-component fluxgate magnetometer used previously.
- 4.5 kHz acoustic beacon and low data-rate telemetry link ($1 bit.s^{-1}$ over ~40 km), as emergency relocation aid.
- Improve thermal insulation of battery packs and use pre-heating within service hangar.

Results from the two engineering trials

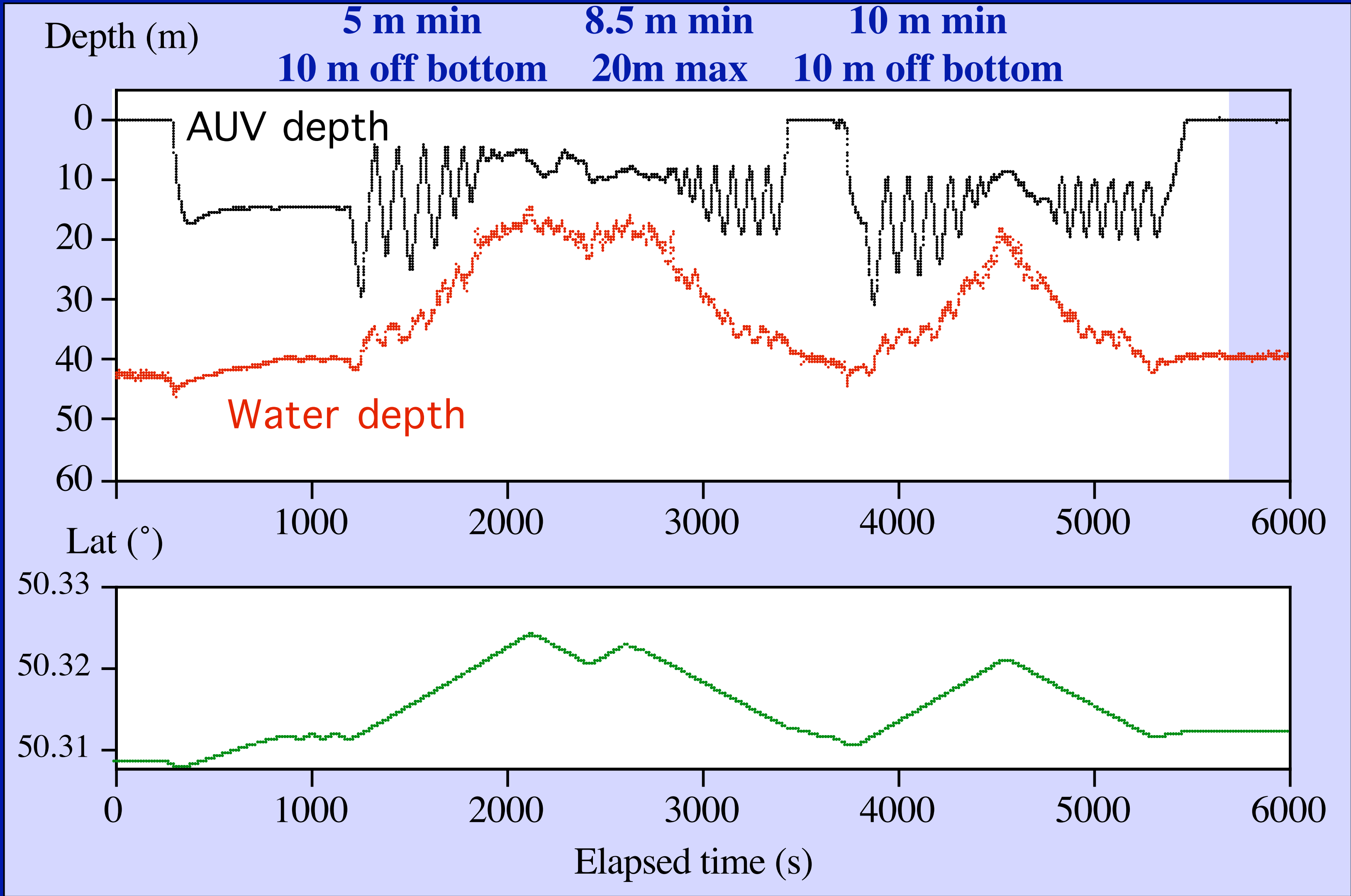
❑ Software

- 22 bugs discovered & corrected
- Successful tests of new modes:
  - Minimum 'Headroom'
  - Iceberg avoidance
  - Constant distance to upper boundary
  - Profiling between upper and lower boundaries
- Confident that logic of the new software worked in the ocean environment, even if ice was simulated.

❑ Hardware

- Collision avoidance sonar ☑
- Multibeam sonar ☒
- Sub-bottom profiler
- Bottom track DVL
  - Acquisition & range ☑
  - Consistency in bottom track ☒
- Digital telemetry over 3 km ☑
- Emergency beacon over 15 km ☒
- Connectors (not an upgrade) ☒

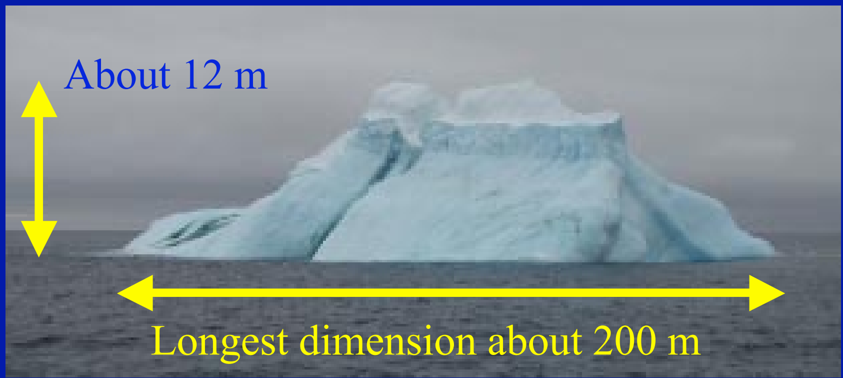
Successful mission segment:
Proving the Yo-Yo Grounding line approach

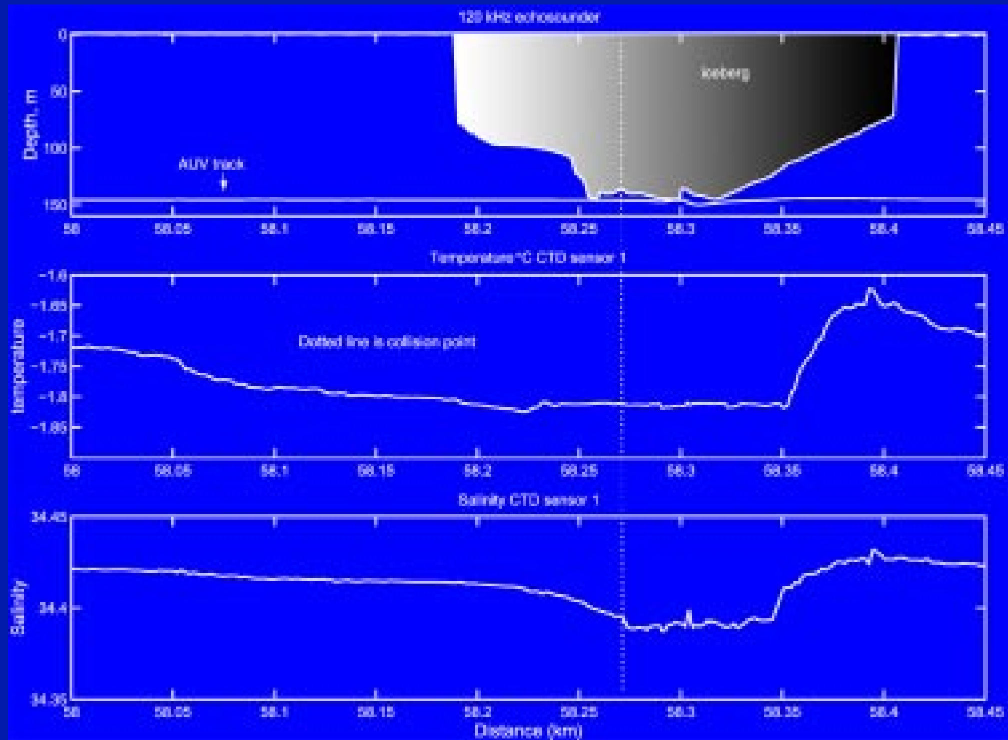


Mission 306: Off Plymouth 50.3˚N 4.4˚W 18 October 2002

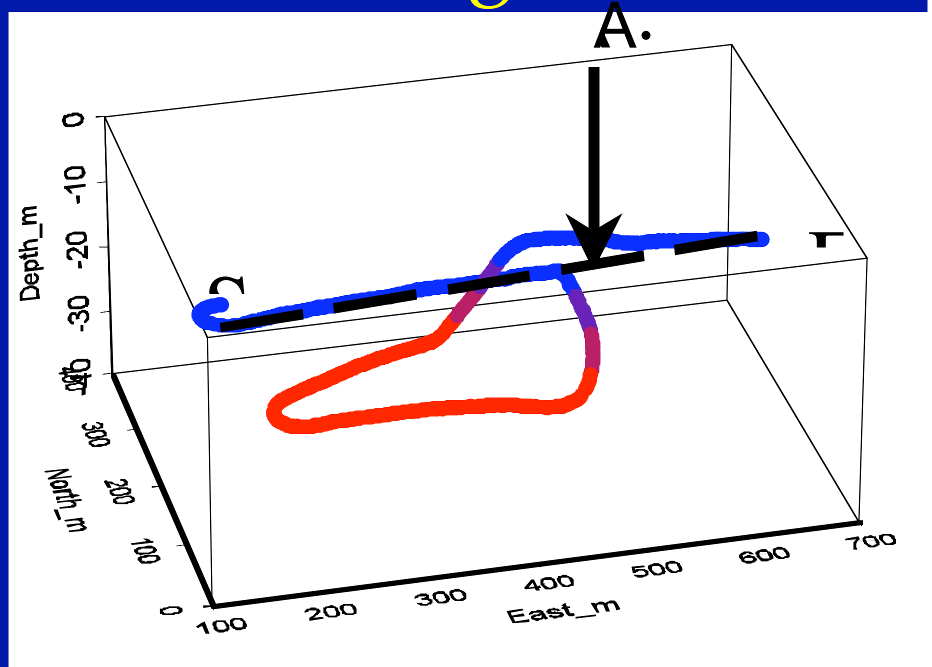
Improved iceberg avoidance required …

A ‘scrape’ with an iceberg in February 2001 - Weddell Sea





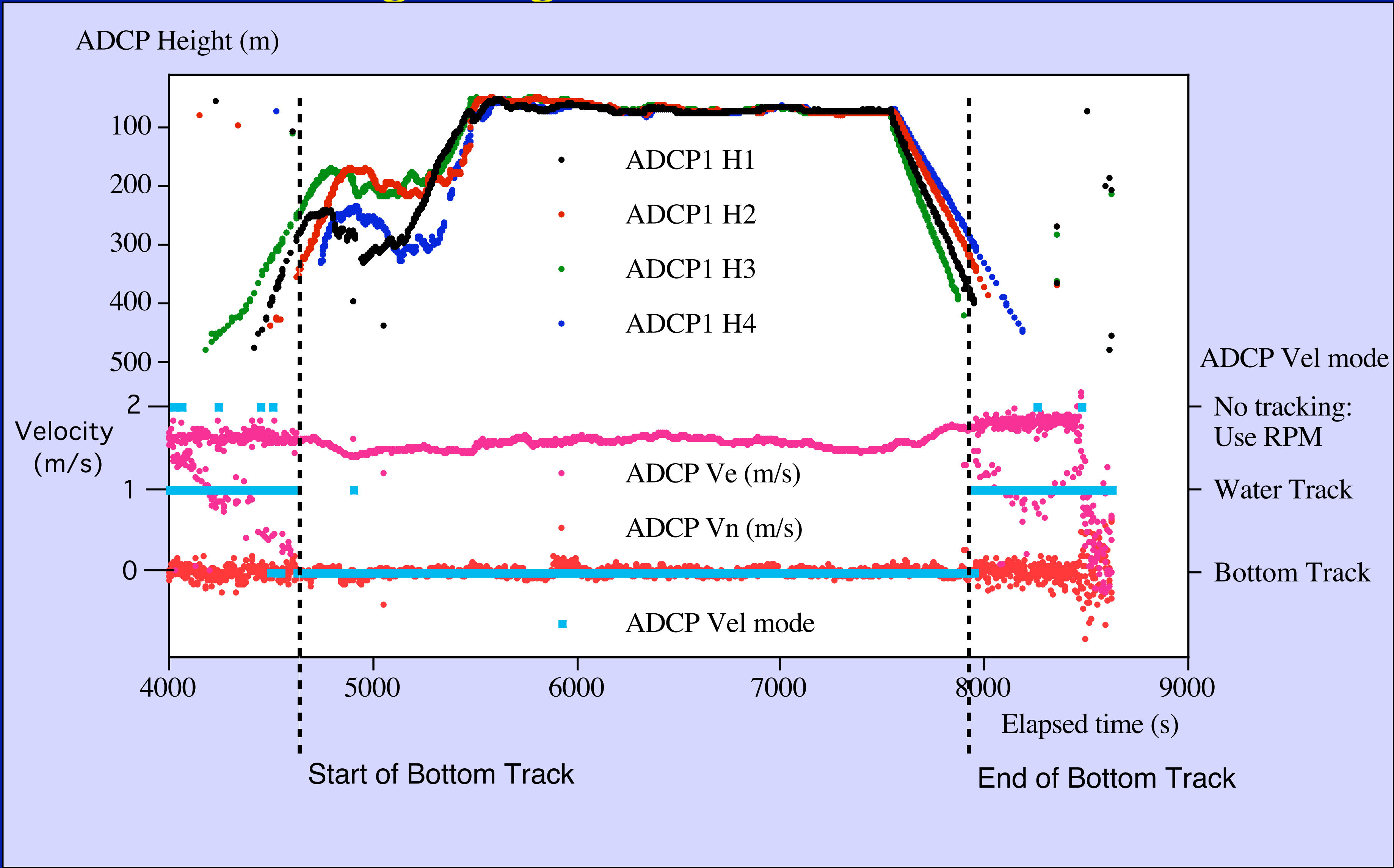
Successful mission segment: An improved iceberg avoidance algorithm



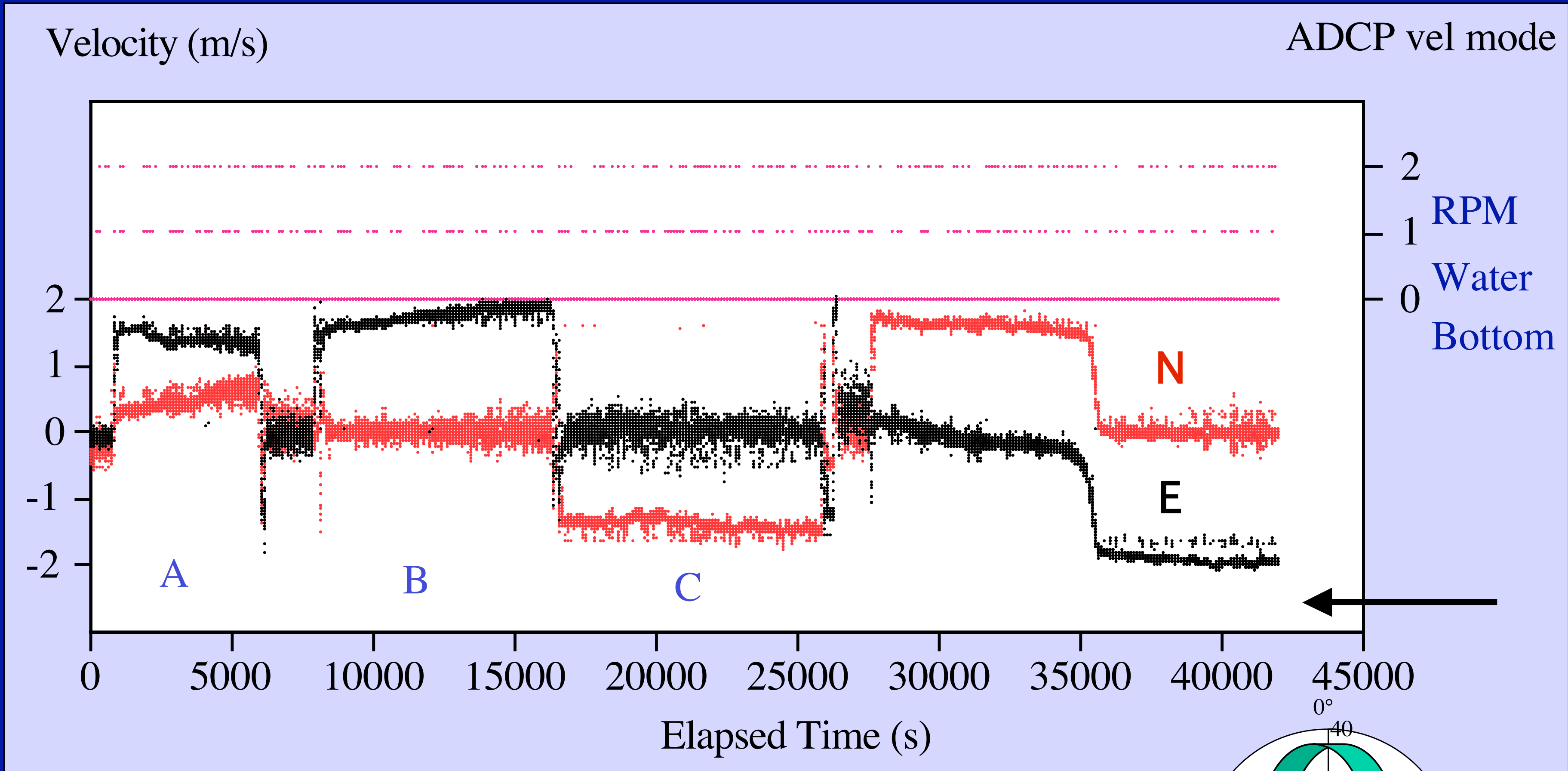
- Generate a synthetic iceberg using compressed air released from a pierced towed weighted & buoyed hose

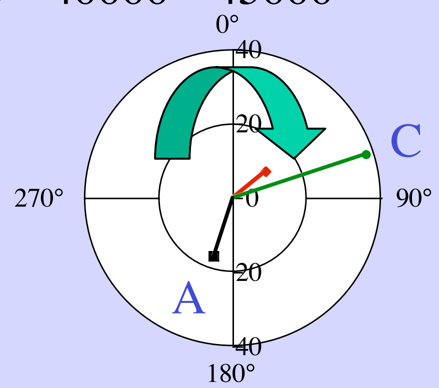
- Approach - blue
- Detection at 'A'
- Change course, and dive - red
- Reapproach, no obstruction, close to previous intended course - blue

Successful mission segment: Long range DVL bottom track

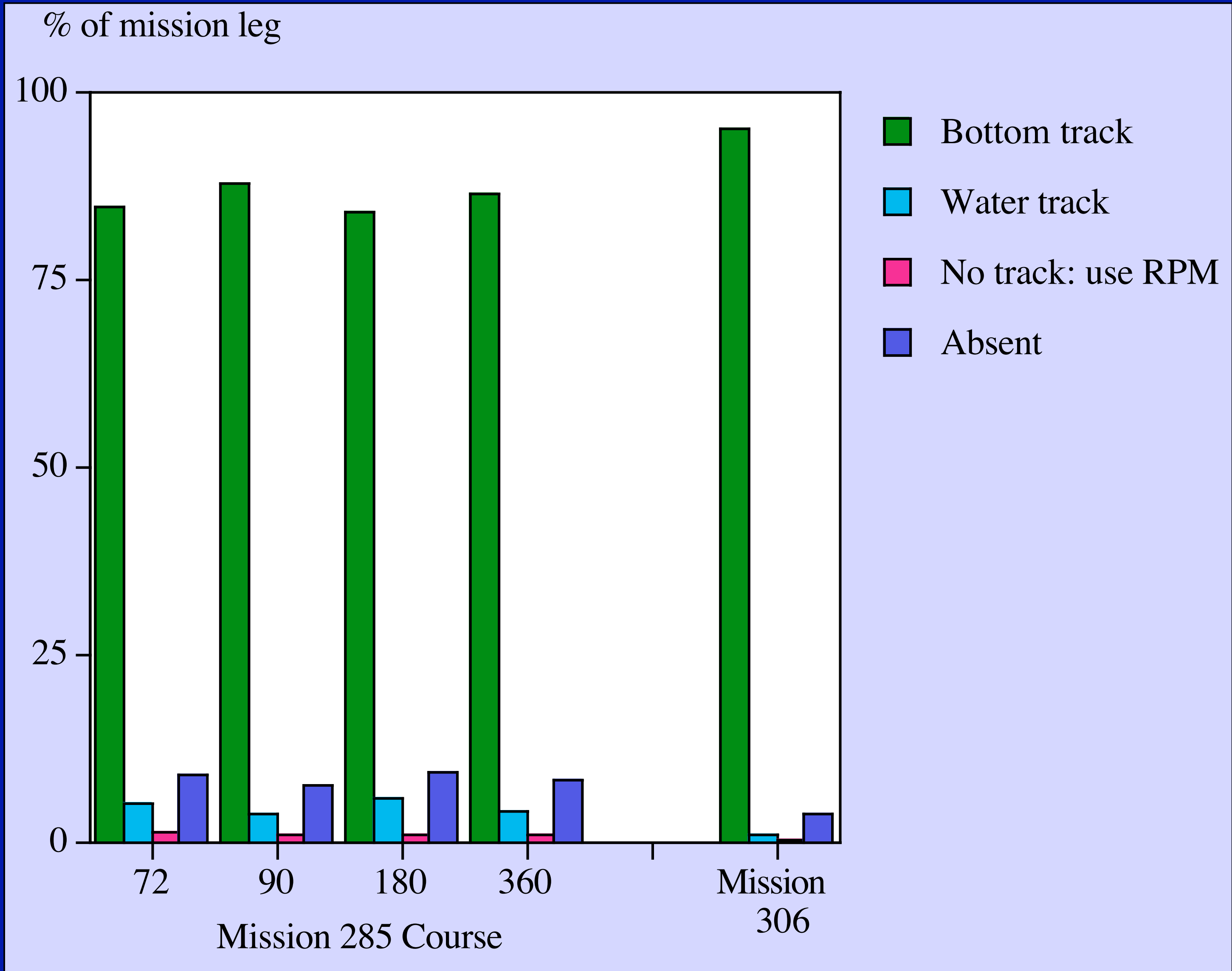


Loss of bottom track in a tidal current





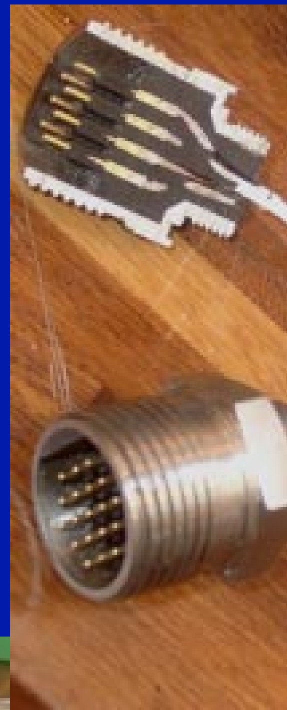
Remaining problem:
Less than 100% bottom tracking



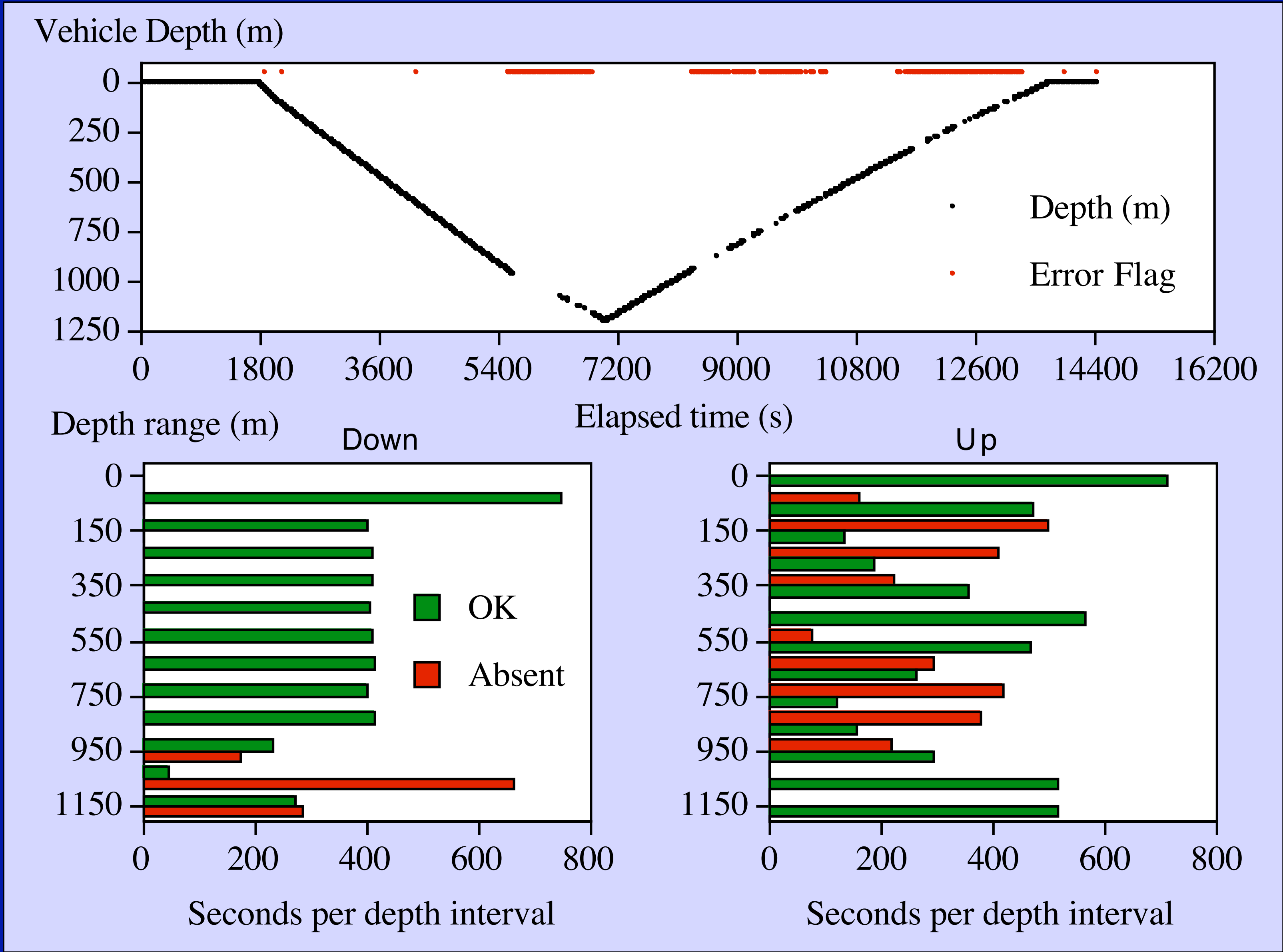
The connector problem …

- ❑ Problem-solving faults leading to premature mission abort led to the conclusion that one or more of the wet-mateable connectors carrying power and data must go open-circuit intermittently
- ❑ These connectors were **not** an upgrade - they had been part of the vehicle from day one
- ❑ The **fingerprint** of the problem has been established, the cause has **not** (beyond unproven hypotheses).
  The solution? Change to a different brand!

Autosub uses 34 pairs of 6 or 19-way wet-mateable connectors to distribute power and network data between individual pressure cases.

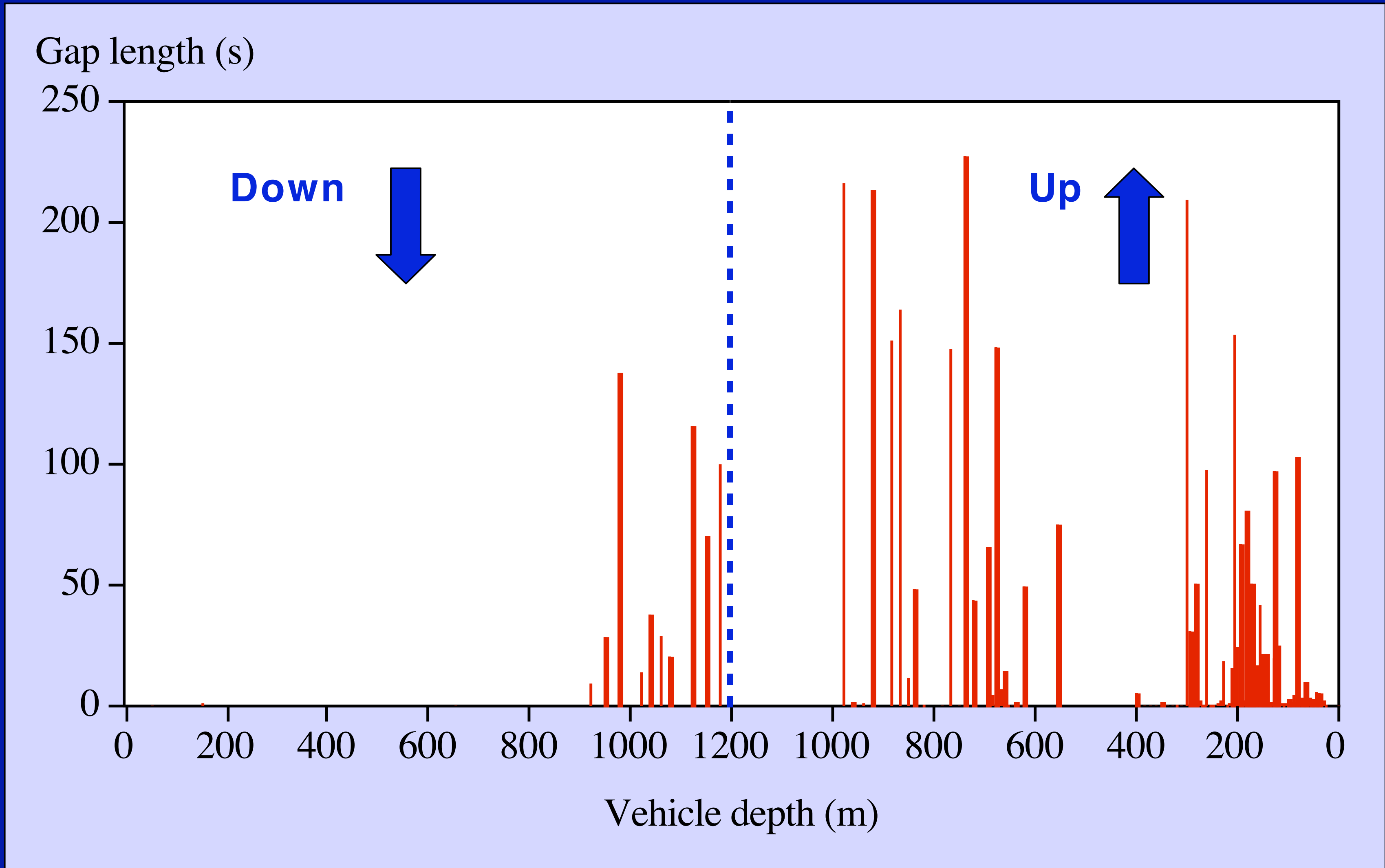


One effect of connector intermittency



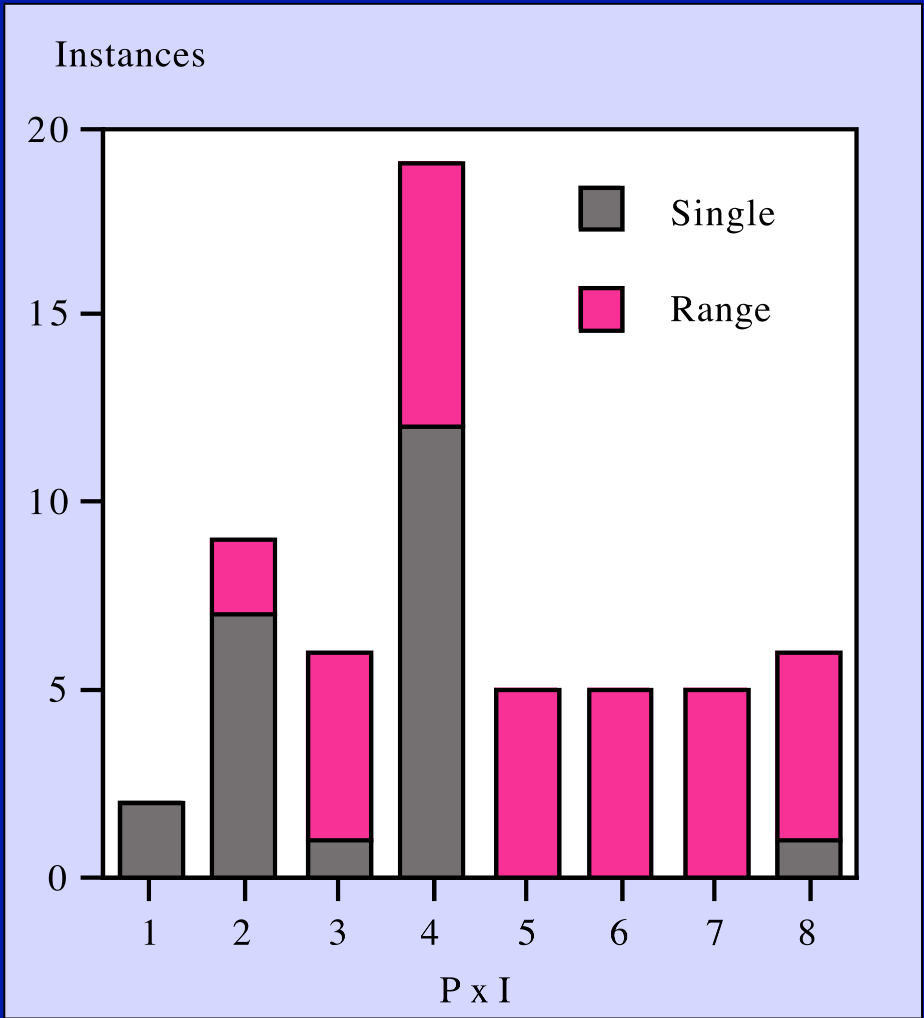
Mission 313 on 13 March 2003 Amundsen Sea

Network disruption duration distribution



Mission 313 on 13 March 2003 Amundsen Sea

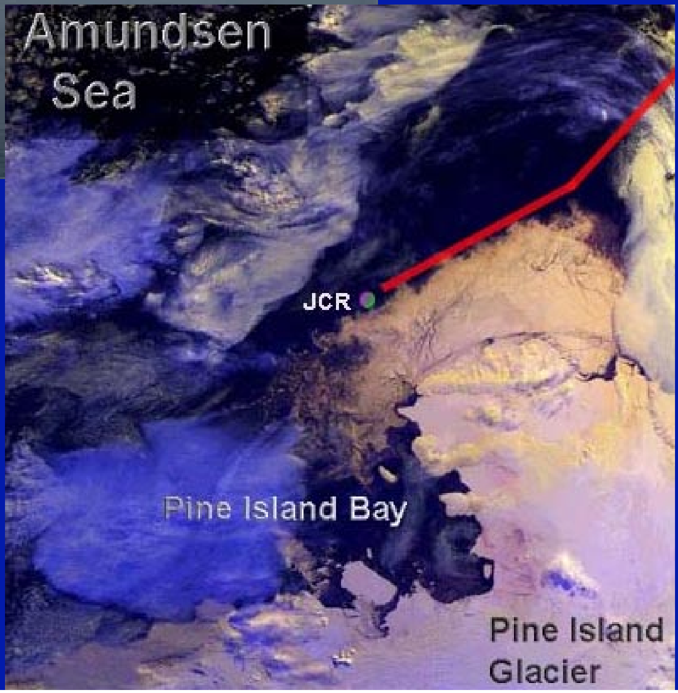
Critical Items List: Probability x Impact



- P x I = 8 Autosub encounters severe unknown bathymetry beyond the ability of the collision avoidance system.
- P x I = 4-8 Collision with vessel during launch/recovery.
- P x I = 4-8 - Local sea ice conditions change during mission.
- P x I = 3-8 - Failure of bulkhead connector(s).
- P x I = 3-8 - Error in ice tracking by vehicle.
- P x I = 3-8 - Error in water column tracking by vehicle.

Autosub performance - Amundsen Sea 2003

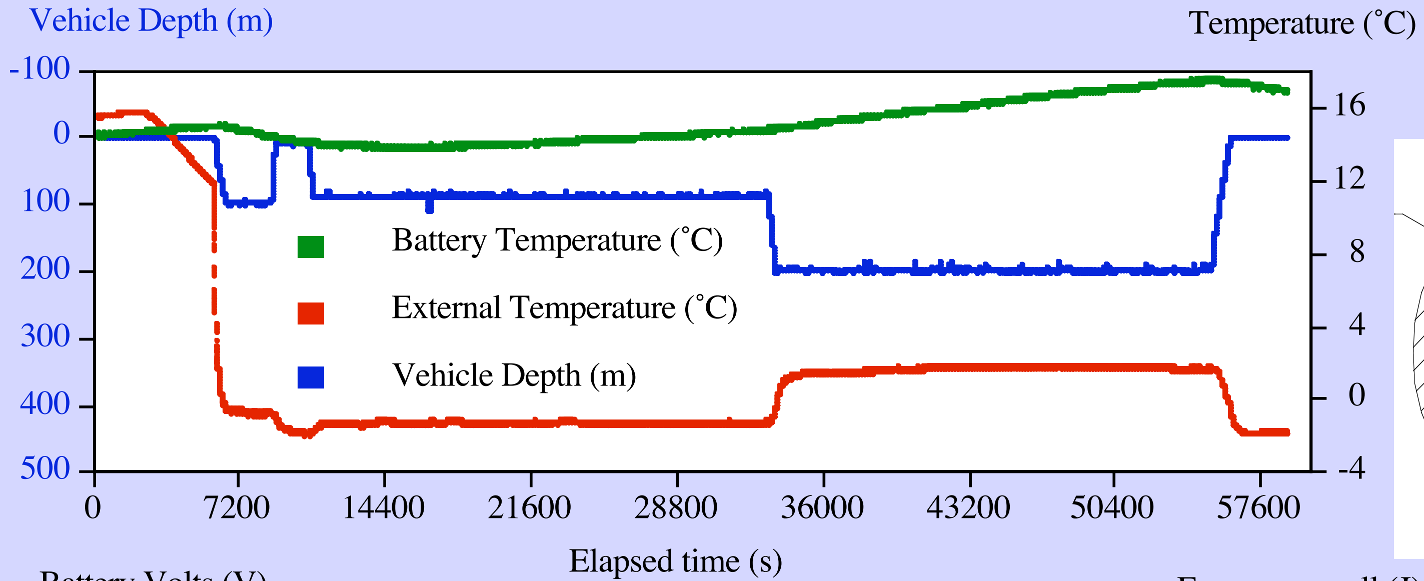
- Missions 307-317 dogged by hardware problems; connector unreliability the worst
- Software fine, bar 3 minor bugs
- Technical problems & concern over ship access & retreat from Pine Island Bay shifted objectives from Glacier to sea ice
- Sea ice observation missions 318-324 covered ca. 220 km
- Problems continued with multibeam sonar, DVL bottom track & water sampler cross-contamination



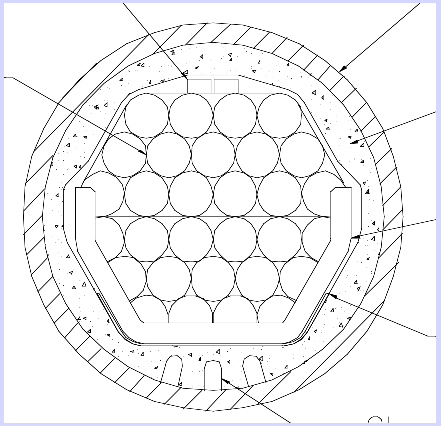
Was the Critical Items List realistic?

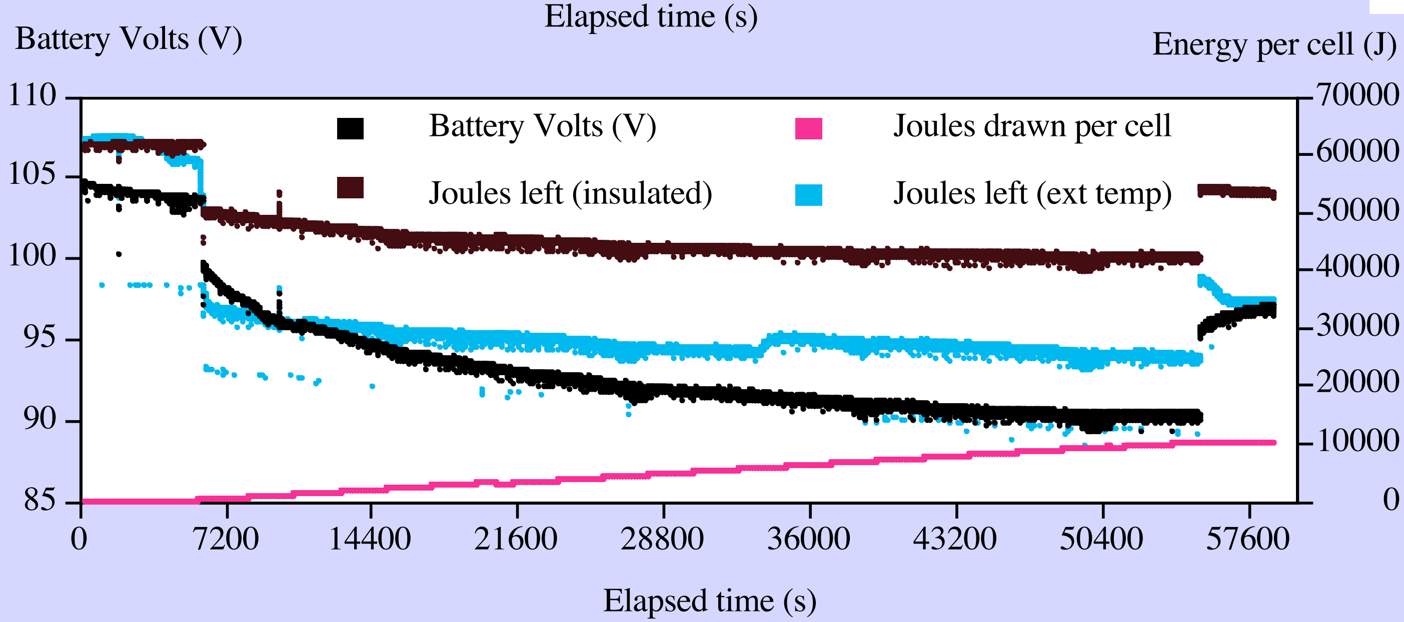
- Autosub encounters severe unknown bathymetry beyond the ability of the collision avoidance system.
- **Not encountered**
- Collision with vessel during launch/recovery.
- **Occurred** - despite procedures, in 35-40kt winds: 2 days downtime + damage
- Local sea ice conditions change during mission.
- **Occurred** - took 8 hours to find vehicle at end of one mission
- Failure of bulkhead connector(s).
- **Occurred** - on several early missions, solution not found; limited depth ops.
- Error in ice tracking by vehicle.
- **Occurred** - bottom track on sea-ice not advisable!
- Error in water column tracking by vehicle.
- **Occurred** - drop-outs in 150 kHz down looking DVL persisted

Effect of insulation on battery performance



Manganese alkaline packs





Cruise time remaining:

16.9 hr (ext)

28.7 hr (ins)

Statistical analysis pre- and post-upgrades

- Method
  - Team logs all faults with the vehicle during missions
  - Categorise into high, medium and low impact and split into those that happened underway or not underway
  - Focus on high impact faults when underway - those likely to lead to loss if operating under shelf ice
- Analysis
  - Most missions complete without a high impact fault when underway, thus they are censored in the analysis
  - For such missions, all that is known is that the time to a high impact fault underway was *at least* as long as the end time of the mission.

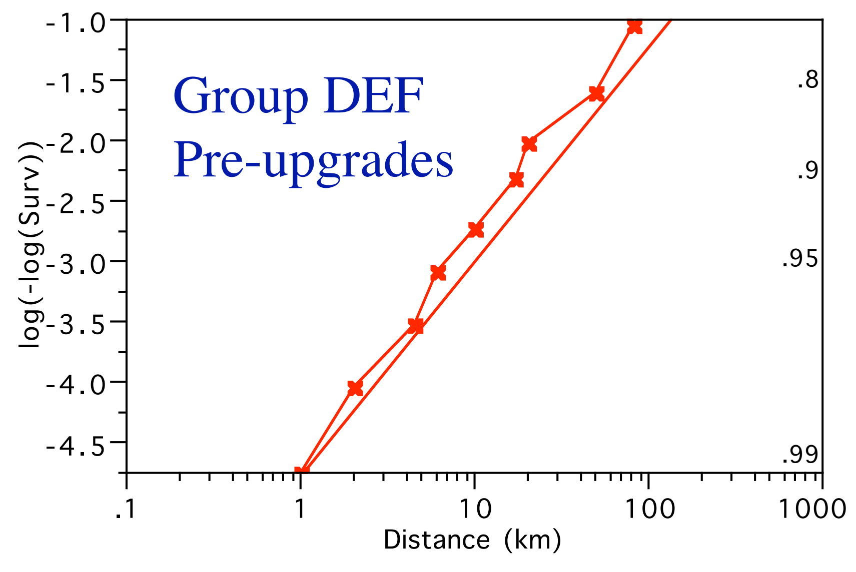
Fit a Weibull parametric model to the data. If the distance to a fault is represented by X, the distribution function – the probability that there will have been a fault before a distance x has been reached is given by

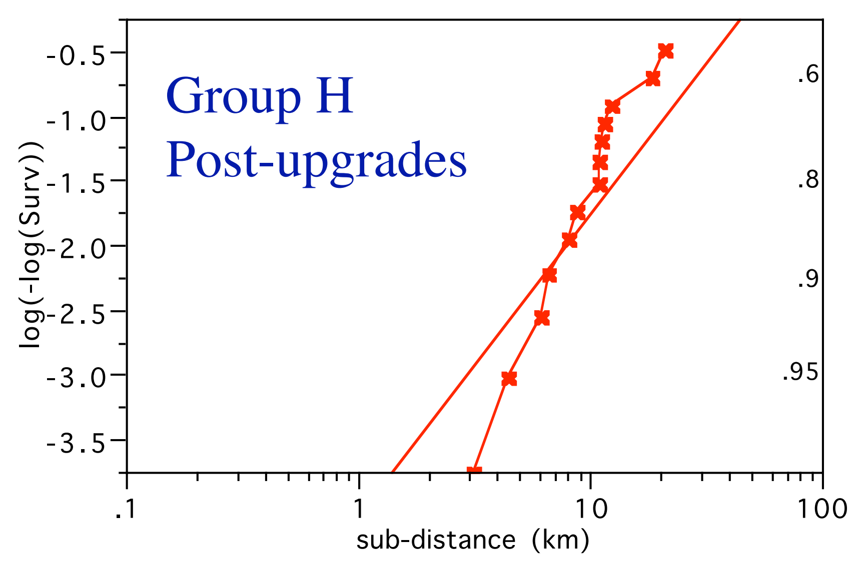
$$\Pr(X < x) = F(x) = 1 - \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right]$$

where α is the characteristic life and β the shape parameter

Pre- and Post-upgrades reliability statistics

Group	α	β	N_{fail}	$N_{censored}$	L95α	U95 α	L95 β	U95 β
DEF	483.1	0.776	9	109	173.4	5105	0.455	1.159
H	55.4	1.016	15	36	33.4	136.7	0.64	1.463





Re-establishing reliability statistics

Mission (km)	1	2	3	4	5	6	7	8	9	10
Set	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)
A	5 (F)	5	5	12 (F)	12	12	36	72	144	144
B	5 (F)	5	5	12 (F)	12	12	36F)	72	144	144
C	5 (F)	5	5	12 (F)	12	12	36F)	72	144	144*3
Weibull	**Set**	**α**	**β**	**N_{fail}**	**N_{censor}**	**L95α**	**U95 α**	**L95 β**	**U95 β**	**Time (days)**
	A	632	0.54	2	8	74.7	7.5×10^8	0.11	1.36	7
	B	217	0.66	3	7	51.2	39223	0.20	1.41	7.25
	C	511	0.58	3	9	96.9	5.6×10^5	0.17	1.29	11

Three hypothetical scenarios for trials missions that set out to re-establish $\alpha > 480$. Upper part sets out mission lengths. An (F) indicates that a mission failed. The 10th mission in set C comprises three segments of 144 km each.

Lower part shows the Weibull distribution parameters and an estimate of the time needed for the missions to be completed

Conclusions

- **The unpleasant surprises …**
  - Overwhelming impact of the latent connector problem
  - Extraordinary effort needed by the team in integrating some 'COTS' sub-systems
  - Just how far out the AUV can be on water-track DR in deep water, and just how quickly ice conditions change
  - How much testing (track km) needed to regain confidence
- **The pleasant surprises …**
  - Software bugs & algorithm quirks were relatively few, tractable and mostly corrected by the science campaign
  - Some COTS items were just that and worked like a dream
  - The effort and time taken on Operating Procedures & Critical Items List meant the team came home with a vehicle