Future options for powering telescopes at Dome A

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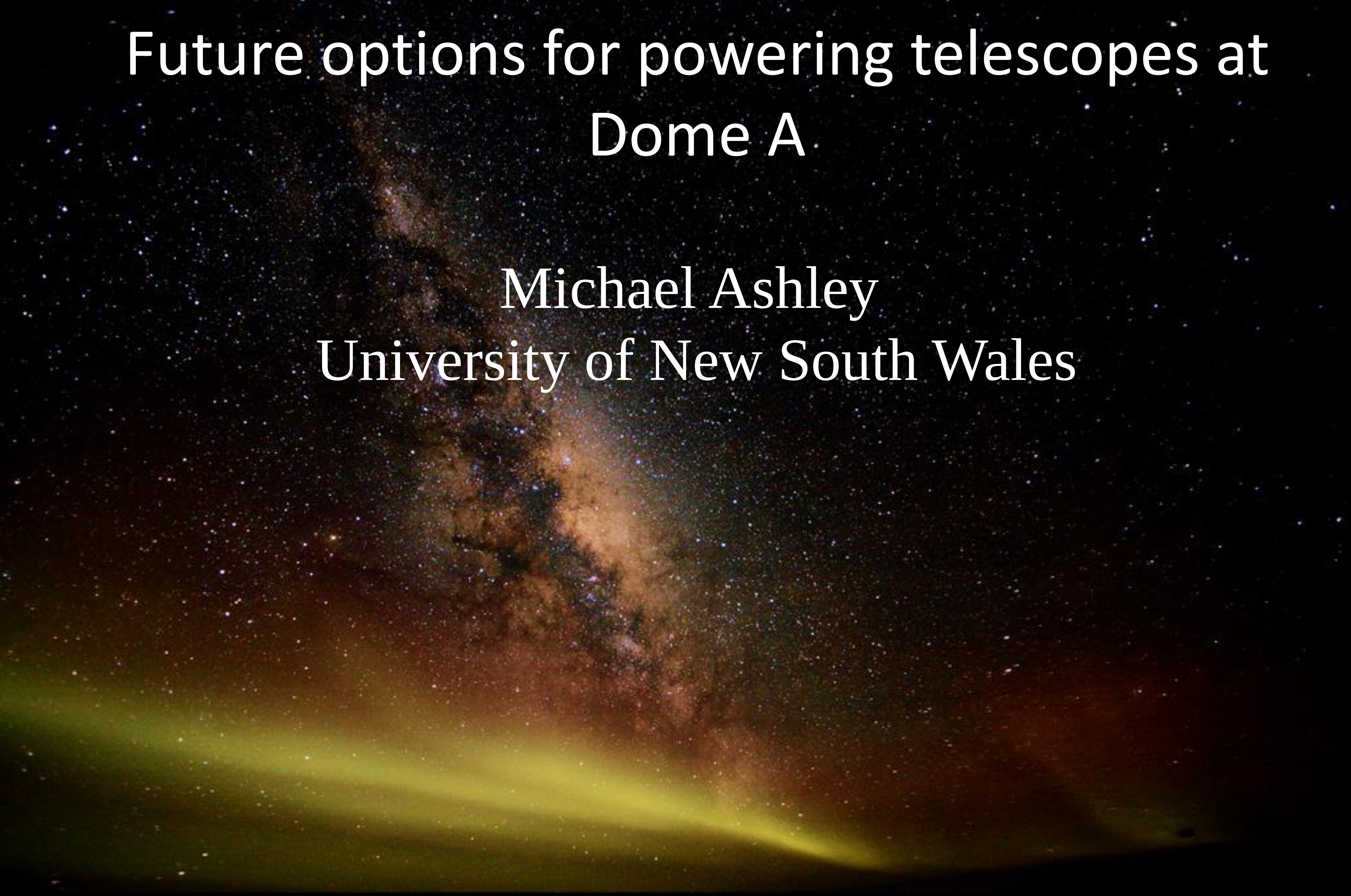


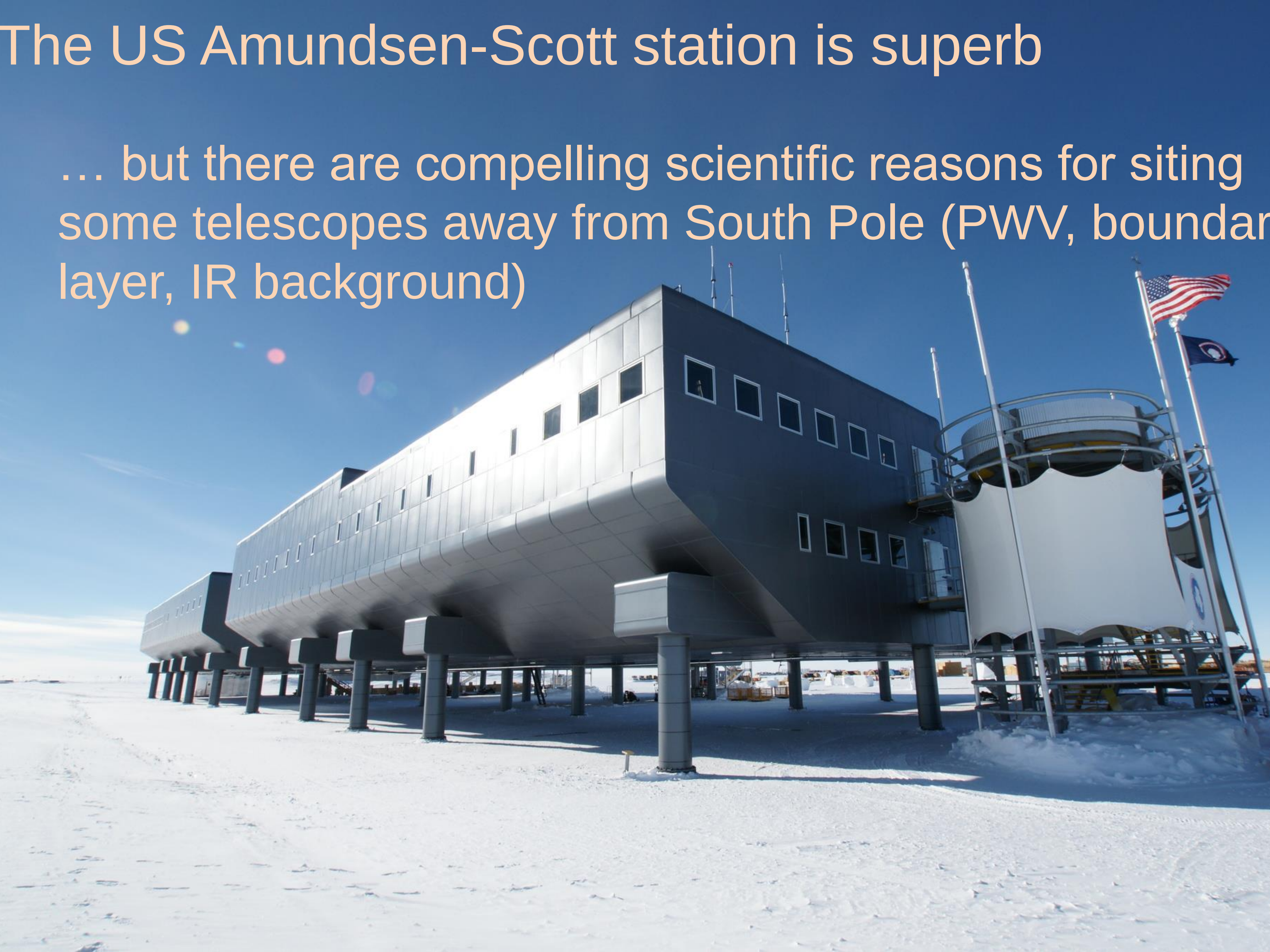
Image: The Galactic Centre and aurora from the South Pole, Daniel Luong-Van, 2010

Why you should care about power

Apart from the obvious point that your *telescopes require power*, it turns out that the provision of a reliable power supply is actually a really difficult challenge that has lots of *lessons for the design of remotely operated telescopes and instruments*.

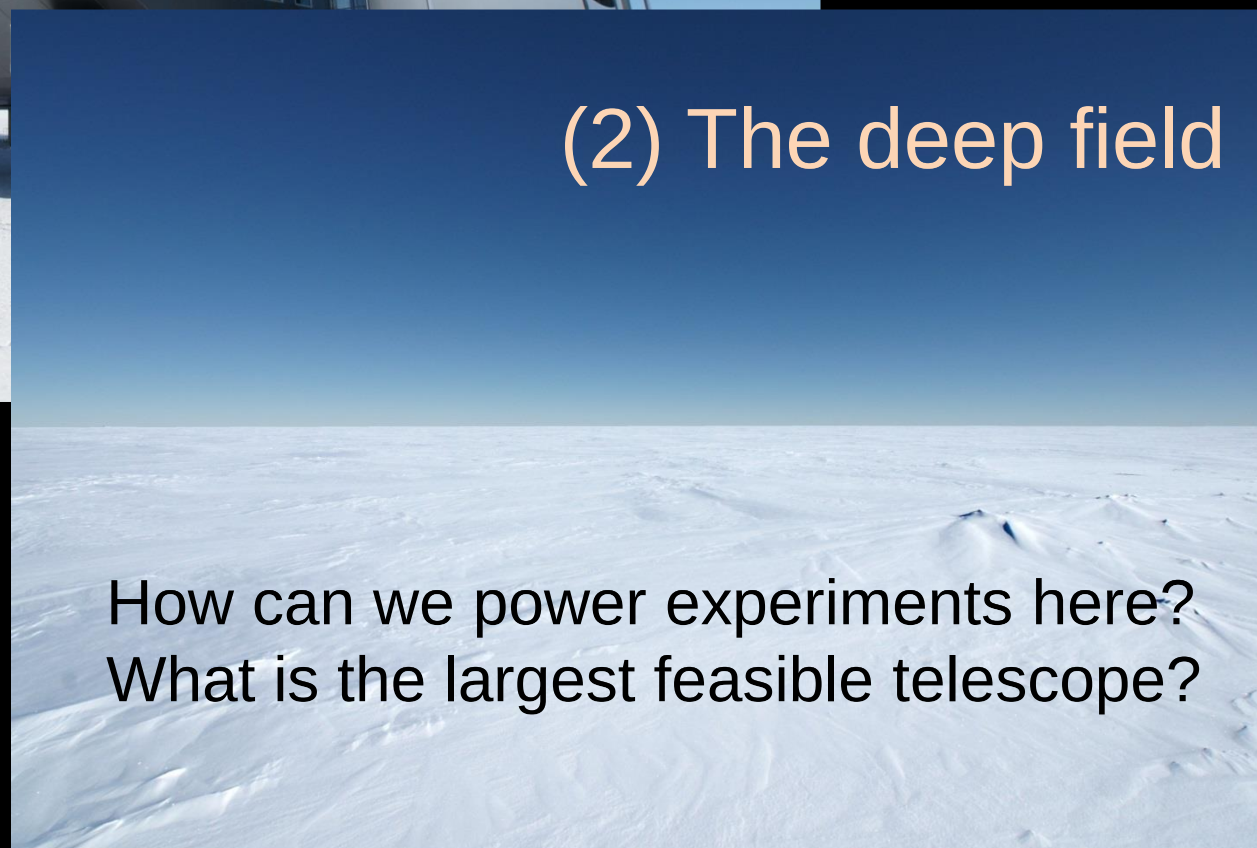
The US Amundsen-Scott station is superb

… but there are compelling scientific reasons for siting some telescopes away from South Pole (PWV, boundar layer, IR background)



Dome F
Ridge A
Dome A
South Pole
Dome C
EAST ANTARCTICA
WEST ANTARCTICA
SOUTHERN OCEAN
KONG HÅKON VII HAV
WEDDELL SEA
BELLINGSHAUSEN SEA
AMUNDSEN SEA
ROSS SEA
ANTARCTIC PENINSULA
PALMER LAND
RONNE ICE SHELF
FILCHNER ICE SHELF
BRUNT ICE SHELF
LARSEN ICE SHELF
ROSS ICE SHELF
AMERY ICE SHELF
SHACKLETON ICE SHELF
FIMBULISEN
DRONNING MAUD LAND
COATS LAND
ENDERBY LAND
KEMP LAND
MACROBERTSON LAND
PRINCESS ELIZABETH LAND
WILHELM II LAND
QUEEN MARY LAND
WILKES LAND
TERRE ADÉLIE
GEORGE V LAND
OATES LAND
VICTORIA LAND
MARIE BYRD LAND
ELLSWORTH LAND
Transantarctic Mountains
South Pole
Amundsen-Scott (USA)
McMurdo (USA)
Halley (UK)
Palmer (USA)
Rothera (UK)
Signy (UK)
South Orkney Is
South Shetland Is
Anvers I.
Adelaide I.
Alexander I.
Peter I Øy
Berkner Island
Shackleton Range
Vinson Massif 4892m
Ellsworth Mtns
Thiel Mtns
Whitmore Mtns
Queen Maud Mtns
Queen Elizabeth Range
Queen Alexandra Range
Executive Committee Range
Mt Erebus
Balleny Is
Subglacial Lake Vostok
Prince Charles Mtns
Scott Mtns
Prydz Bay
Davis Sea
Dumont d'Urville Sea
Antarctic Circle 66°34'S
80°S
70°S
90°W
90°E


Two regimes: (1) winterover station
(three 100-1000kW diesel engines)


(2) The deep field
How can we power experiments here?
What is the largest feasible telescope?

How do we provide 1-10 kW continuously for a year, with no human on site?

Renewables

Solar

Easy to build/deploy, no moving parts, highly reliable.

No sun during winter.

Wind

Relatively simple. Should have a long life with careful design.

Velocity-cubed dependence on wind. Long periods of calm on the plateau. Mixed success in the field.

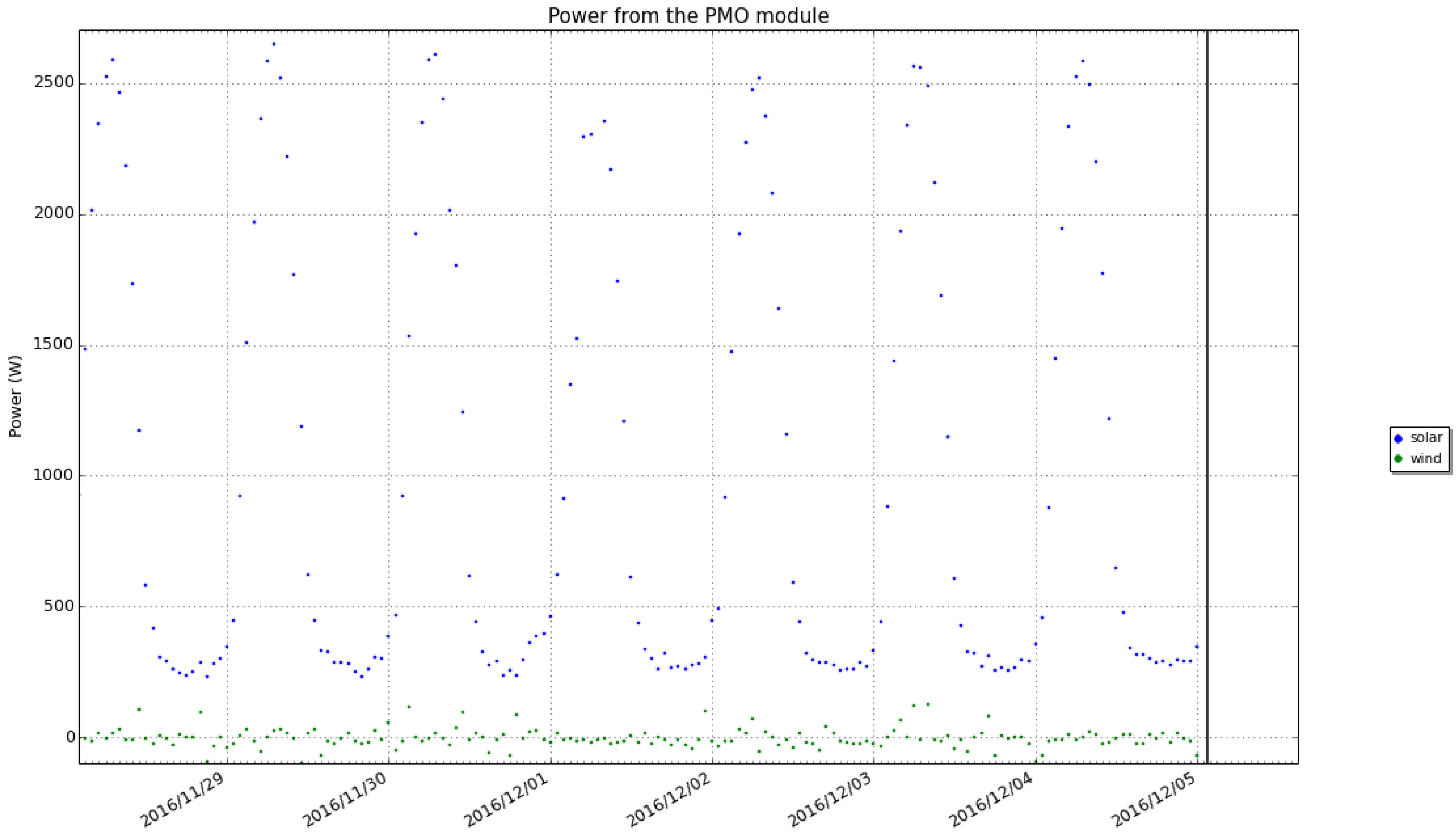
Batteries

Simple, easy to deploy.

You need many *many* tonnes of batteries. You have to keep them warm. In practice, only 1 day of storage is practical.

PLATO-A solar power from the PMO module over a week in summer

- The solar power peaks at 2.6 kW, and averages 1 kW over summer.
- Solar power is an excellent way of stretching the use of fuel reserves over winter.



Fossil fuels

Diesel engines

Kerosene stores a huge amount of chemical energy

Engines are mechanically complex, need regular maintenance, oil changes.

Thermoelectric generator

No moving parts

Highly inefficient. Numerous single point failures. Hasn't got a good record in the field.

Fuel cells

Should be reliable and clean

Not ready for prime time. Exhaust/membrane clogging. About 1/3rd the power density of kerosene.

Microturbines

Mechanically simple, long life, reliable, low pollution

Less efficient than diesel; very costly; software issues.

Nuclear

Radioisotope thermal generator

Simple, reliable, bulletproof.

Costs many tens of $millions per kW, if you could buy it.

3rd-generation nuclear fission reactor

Huge power output, fuel is compact and lasts for decades.

Uneconomic. Unproven. Safety issues.

Historical and future power requirements at Dome A

2008-2015 1kW average over the year, with 2kW peak; plus 1kW solar over summer

2016 An additional 2.5kW solar

2017 As above

2018 As above, with the possible addition of a prototype 5kW diesel engine for testing, and with the possible addition of a power module from Purple Mountain Observatory (extra 1kW?)

2019 We would like to have at least 3kW continuous to supply two AST 3 telescopes and an infrared camera

2022 Aiming for 10-15 kW or more to support KDUST and DATE-5

AASTO at South Pole
50W power budget
1996

AASTINO at Dome C; 2004
500W power budget

PLATO (PLATeau Observatory)

Redundant diesel engines, large oil reservoir to increase maintenance interval

Solar panels (1kW PLATO; 2.5kW Purple Mountain Observatory)

LiFePO4 batteries

PLATO leaving UNSW, Sydney, Australia, November 2007

Green → the Engine Module (6 diesel engines, 4000 litres Jet-A1)

Yellow → the Instrument Module (experiments that need to be warm)

PLATO times four

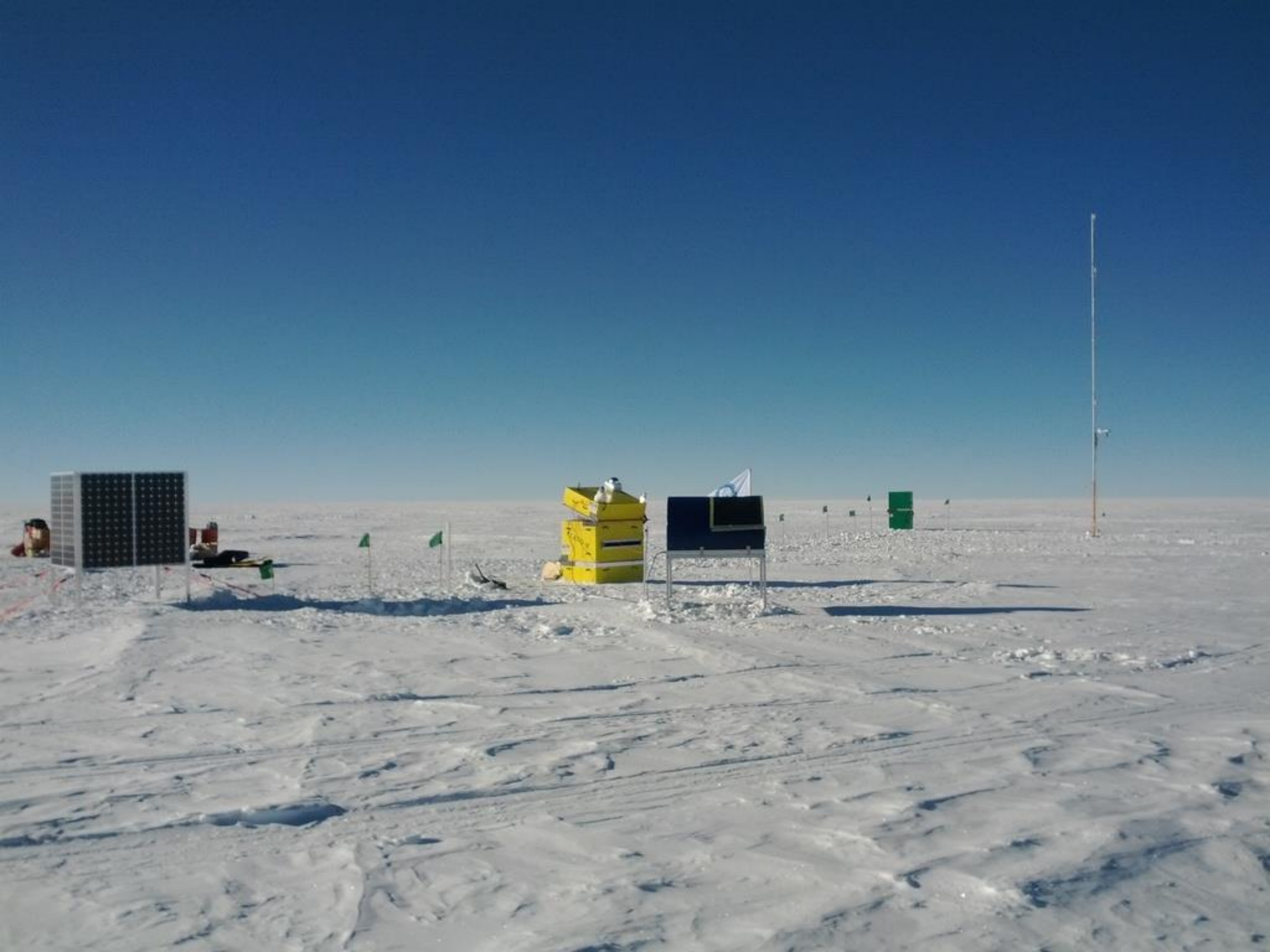
- The “original PLATO” (based on a 10-foot shipping container) went to Dome A in late 2007.
- A new lightweight design, PLATO-F, was sent to Dome Fuji in late 2010, and PLATO-A to Dome A in late 2011.
- A slimmed-down two-engine model, PLATO-R has been at Ridge A since Jan 2012.
- We have accumulated 17 years of combined operation of all the PLATOs.
- For 18 months from Jan 2013, we had three PLATOs running simultaneously on the plateau.

PLATO-F at Dome F, January 2013

Jan 2013, Hirofumi Okita

PLATO-A at Dome A, January 2013

Jan 2012, Giguo Tian



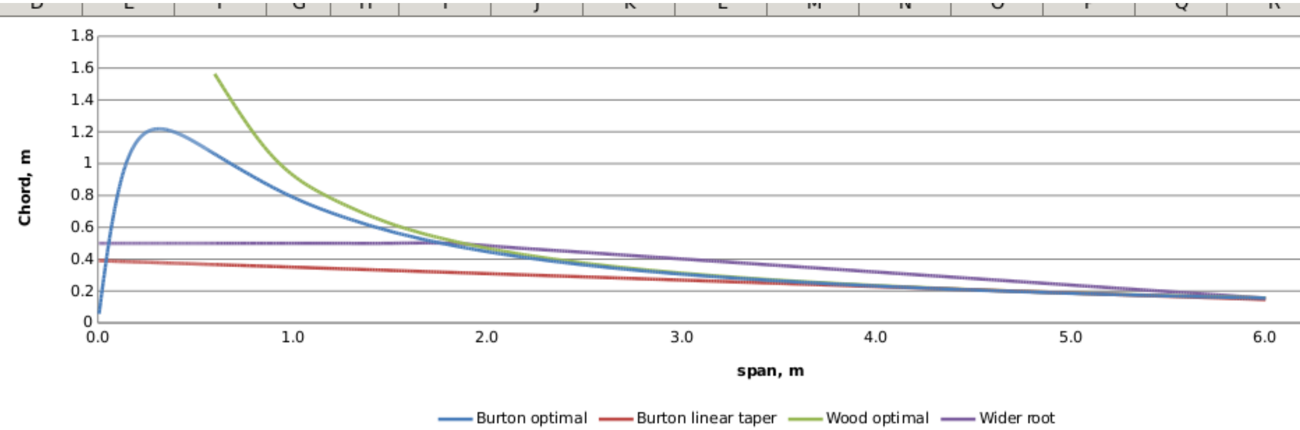
Next-gen PLATO improvements

- Ease of servicing.
- Improved modularity (e.g., single engines in individual modules; battery packs in individual modules).
- Higher power (10kW or more).
- External fuel tanks.
- Wind turbine?
- Microturbines rather than diesel engines?
- An initial attempt at funding through the ARC Linkage Project scheme in 2016 was unsuccessful. However, the referee reports were very supportive, and we believe that with confirmation of a commitment from China to KDUST and DATE-5, our next attempt is likely to be successful.

Wind turbine design

- While the wind speeds are low at Dome A, wind is an attractive low-cost, zero-pollution renewable energy source.
- We have designed a carbon fibre blade for optimal performance at Dome A.
- The blade length is 6 m, for ease of transport in shipping containers.
- We envisage a 3-bladed turbine with a hub height of 15 to 20 metres, no gearbox and a simple yaw mechanism. Ease of maintenance is a high priority.
- *During 2017 we have two teams of ten final year Mechanical Engineering students working on the design.*
- We will have electrically heated bearings, and the ability to spin-up the turbine to overcome stiction.

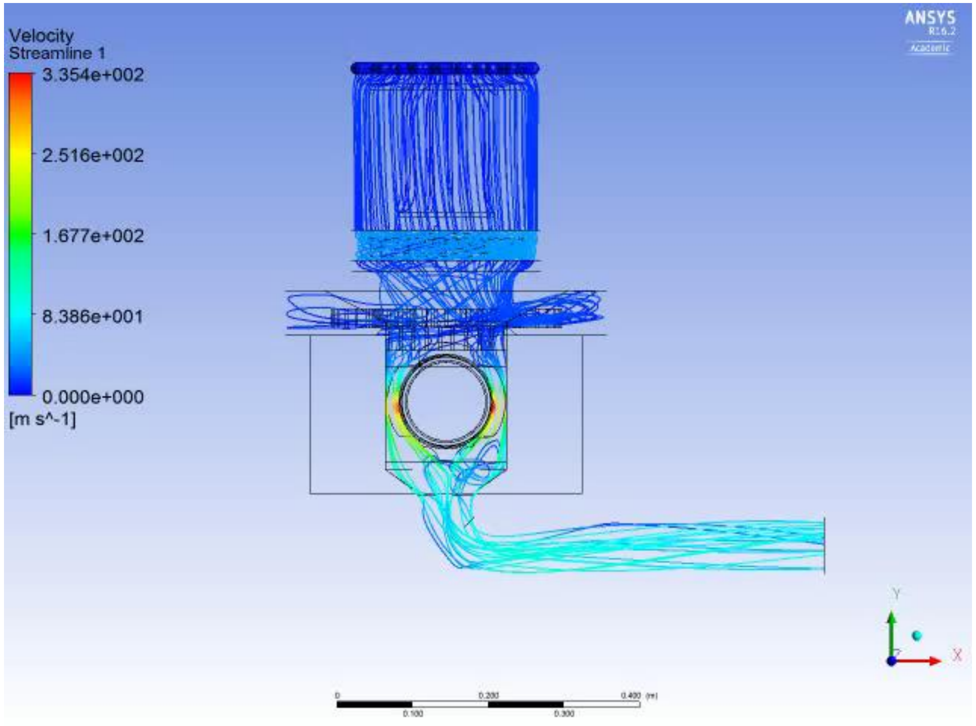
Variables		
Turbine radius	6	m
Design wind speed	4.5	m/s
Tip speed ratio	9	
# blades	3	
Air density, ρ	0.735	kg/m^3
Angular velocity, Ω	6.8	rad/sec
	64.458	RPM
Tip Speed	40.5	m/s
Planform area (optimal)	2.581	
Planform area (linear)	1.610	
Cl	0.882	
Maximum gust wind speed	35	
Drag coefficient, Cd	1.5	

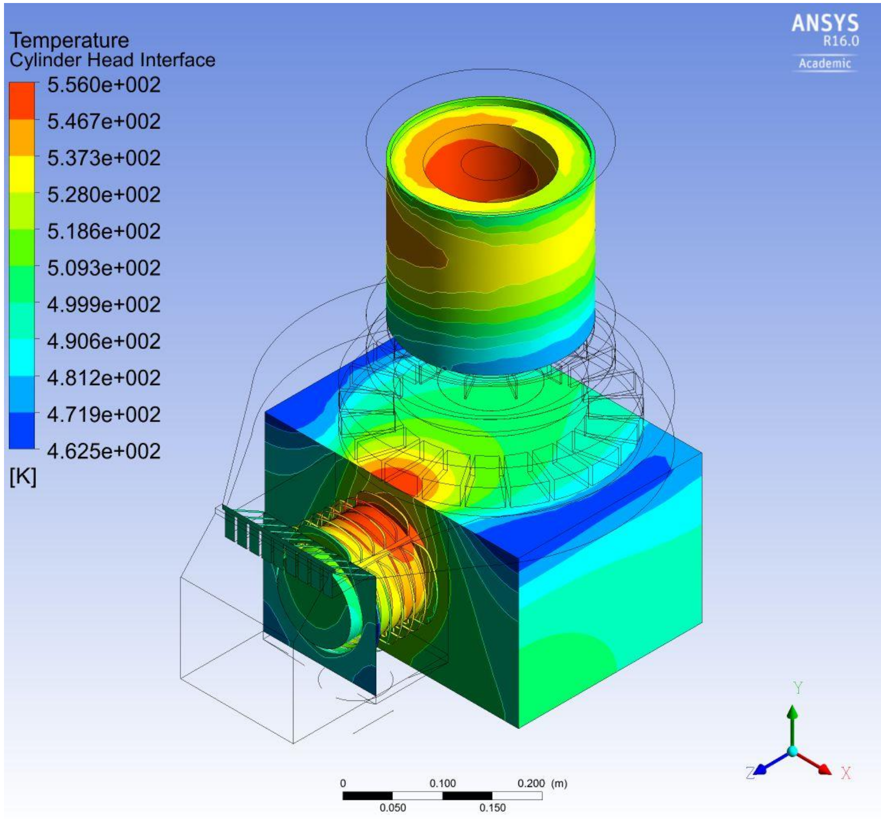


				Burton optimal													
Station	r	μ	λr	σλCl	λμ	λ^2μ^	σ	chord	delta A	c/R	alpha	tanφ (rad)	φ (deg)	β	cu	chord	c/R
0.10%	0.0	0.00	0.0	0.035974	0.01	8E-05	0.005	0.056949	0.016	0.009491	7.92	0.02699	1.546047	-6.4	0.065106	0.391	0.0651
1%	0.06	0.01	0.1	0.336122	0.09	0.008	0.042	0.532102	0.043	0.088684	7.92	0.260505	14.60129	6.7	0.06474	0.388	0.0647
2%	0.12	0.02	0.2	0.568419	0.18	0.032	0.072	0.899844	0.060	0.149974	7.92	0.471286	25.23387	17.3	0.064332	0.386	0.0643
3%	0.18	0.03	0.3	0.694277	0.27	0.073	0.087	1.099085	0.069	0.183181	7.92	0.609917	31.37972	23.5	0.063925	0.384	0.0639
4%	0.24	0.04	0.4	0.751375	0.36	0.13	0.095	1.189475	0.072	0.198246	7.92	0.682163	34.30035	26.4	0.063518	0.381	0.0635
5%	0.30	0.05	0.5	0.769246	0.45	0.203	0.097	1.217767	0.073	0.202961	7.92	0.706344	35.23524	27.3	0.063111	0.379	0.0631
6%	0.36	0.06	0.5	0.765079	0.54	0.292	0.096	1.21117	0.072	0.201862	7.92	0.700631	35.01629	27.1	0.062704	0.376	0.0627

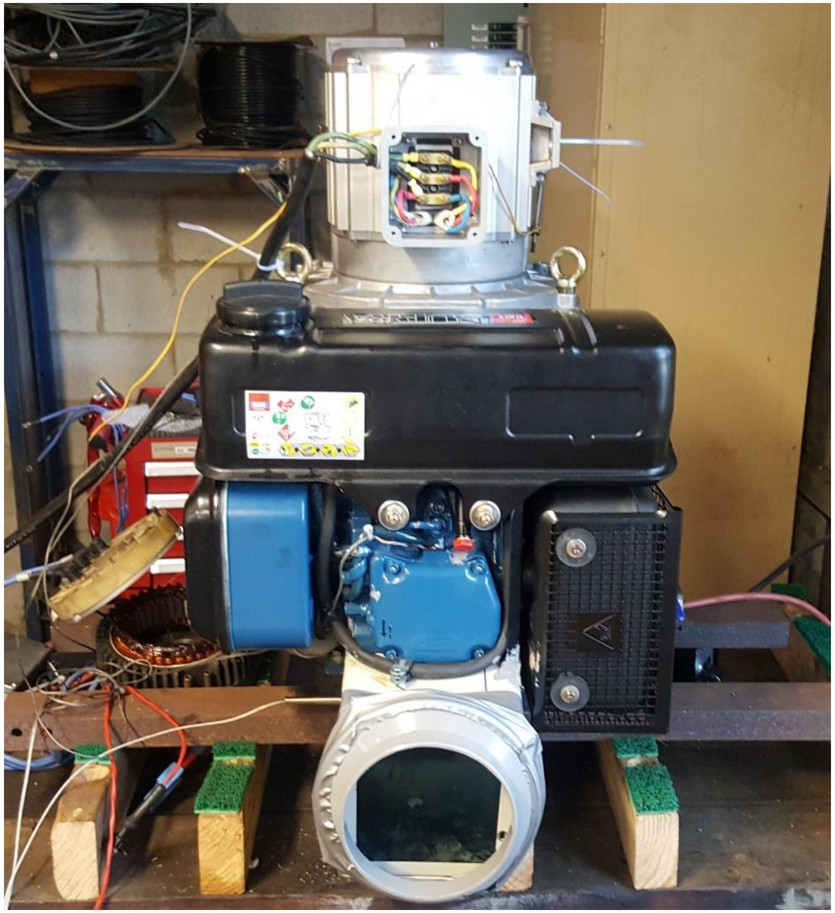
PLATO-A new modular engine design

- While solar and wind are useful, diesel engines are likely to be necessary.
- We are designing a 5 kW power plant (10kW at sea level) that can be readily installed at Dome A with much lower effort than the existing 1 kW units.
- Mechanical engineering students at UNSW have been working on the thermal design of an enclosure.



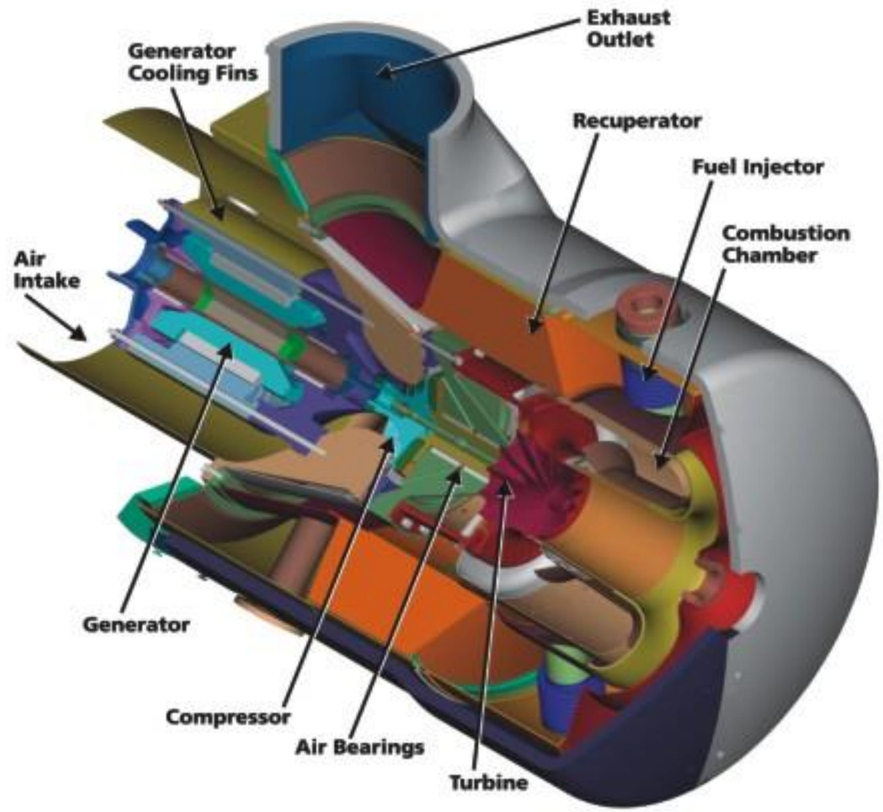


PLATO-A modular engines - laboratory testing



- An instrumented Hatz 1D-90V engine with 10kW alternator (5kW at Dome A altitudes) is being tested in our lab for comparison with computational fluid dynamics models.
- The photo at right shows air flow measurements taking place in November 2016.

Capstone microturbine



Getting the data back?

Iridium modems, 20MB/day.

Iridium OpenPort: 128 kbps.

Iridium NEXT (complete replacement of all 66 satellites from 2017-2018).

A Ka-band CubeSat could provide 250 GB/day store-and-forward via Svalbard in Norway

PLATO design philosophy

- Reliability, redundancy, reconfigurability.
- Minimise single point failures.
- CAN (Controller Area Network) communications.
- Extremely reliable supervisor computer.

The three Rs: reliability, redundancy, reconfigurability

- Striving for reliability is crucial, but insufficient for a successful operation.
- Things always break.
- The key is to eliminate single point failures.
- You must build in redundancy *and* reconfigurability, i.e., it should be possible to route around any failures.
- PLATO has been quite successful at this, e.g., over 7 years of continuous uptime at Dome A, with annual servicing.

An example of the importance of reconfigurability

- In early May 2014, the PLATO-A Engine Module started to become very cold.
- Investigation showed that the ventilation fans were stuck on.
- This in turn was due to the failure of a “high-side switch”, an electronic part. At the time of building PLATO-A the world was gripped in a global financial crisis, and some electronic parts were impossible to come by. We had to use a slightly lower-spec component, which had a higher failure rate.
- The solution: we had independent control of the 24VDC power supply feeding the high-side switch, so we altered the control software to cycle the 24VDC.

Some things have gone wrong

- Power supplies are a major problem. We have had failures of many different types, including top brands such as Vicor and Lambda-TDK.
  - "Genetic diversity" is good
- We have had many disk drive failures, most likely altitude related. No failures with helium-pressurized disks.
- Battery management system failures.
- Iridium modem short circuit.
- Manufacturer's firmware is often buggy.
  - Have everything under your control.

Some things have gone right

- The supervisor computers have been bulletproof – zero failures with 8 in the field, over 30 years combined uptime.
  – The reason? milspec design, soldered-in RAM, read-only filesystem, hardware watchdog timer, Linux.
- Hatz 1B-30 & 1B-40 diesel engines.
- Solar panels – 3kW at Dome A, 1kW at Dome Fuji and Ridge A, zero failures.
- Iridium OpenPort. Three systems in the field, only minor issues.

Key design decisions for reliability

- Check for single-point failure modes and eliminate them as far as practical.
- Provide multiple backups of all systems, with genetic diversity.
- Make the system modular, and remotely reconfigurable.
- Strictly minimise the number of critical computers. Ideally, only one computer should be needed.
- Avoid Windows, use Linux.

The most crucial component in a remote system is the "supervisor computer" and its internet connection

- Use reliable hardware (e.g., milspec single-board computers with soldered-in memory).
- Use a hardware watchdog timer to recover from software lock-ups.
- Use a Debian Linux system with a read-only filesystem.
- Don't use Windows – who knows when it will reboot to "install an update"? Also, it wants to communicate to Microsoft servers.
- Keep the operating system and application files in on-board flash memory.
- Use 8TB (or larger) helium-filled disk drives for large volumes of data storage. Consider a custom file-system as simple as writing raw sectors to the disk in sequence – this makes data recovery much easier if the disk develops bad sectors.
- My personal preference is not to use RAID, just keep two copies. E.g., power up a backup disk, copy the data across, and then power down the disk.
- Have at least two supervisor computers, only one of which is needed.
- DO NOT have lots of computers, all of which are required.
- Consider having two separate LANs, each with redundant power supplies for their network switches.

Commercial-off-the-shelf, or in-house?

- For many applications, COTS is far more cost effective than designing something yourself. However, you have to be careful, e.g.,
  - Proprietary firmware can be really problematic, of very poor quality, and with unexpected behaviour that can be impossible to fix. E.g., a battery charger unit we used assumed that if the temperature ever dropped below -20C, it was a sensor error, and the temperature was set to +20C.
- With in-house designs you have complete knowledge of the system, which can be invaluable.
- COTS systems often use Windows GUI programs to control them. These programs are extremely difficult to use over satellite links, and if you need to update one, you might need to transfer a gigabyte or more of random DLLs.
- With our Dome A operations, proprietary firmware has been possibly the biggest problem we have faced, and we have moved to using an entirely in-house design for our critical systems (e.g., the CAN bus devices and battery management system).

Software is *really* important

- The importance of a clean software design is paramount.
- Use git for keeping track of software revisions.
- When developing firmware, store the git ID in the firmware so that you know exactly how to generate the code from the source (including all Makefiles and options configured in IDEs). Every "git commit" should store the updated git ID in a file included in the source code (but not itself stored in git).
- Prefer command-line compilation over IDEs.
- Provide an easy way to update the firmware, ideally able to be done remotely, else with a programming device on-site that doesn't require the equipment to be disassembled to get to the interface. For our battery management system we use infrared communication that allows all 106 units to have their firmware updated in parallel.
- You won't be able to write a supervisory program that will respond to all possible failure modes. A good approach is to gradually automate systems as you gain experience when things go wrong. Provide mechanisms to alert people when human attention is needed. When I started writing the PLATO supervisory script, it would need attention on a daily basis, now it can run for typically 2 months at a time with no issues.

Genetic diversity

- Use solutions that are "genetically diverse", i.e., use different approaches in parallel, and use equipment from different suppliers.
- As an example, we used a dozen or so 400W DC-DC converters made by Vicor. While these are excellent products, and Vicor has a very high reputation, they weren't kidding with their minimum storage temperature. We found that all of the devices died over a period of 2-3 years, following occasional cold-soaks to below -60C. The apparent cause is differential thermal expansion between the epoxy encapsulation and the components on the printed circuit board.
- Fortunately, we had 1kW DC-DC converters made by Meanwell, that kept working.
- Batches of components from suppliers can all fail early.

Protect against rogue instruments

- The power system, supervisor computer, and satellite communications are the critical components. They should prioritise keeping themselves running, and have the ability to shed power to instruments if necessary.
- Instruments should be able to survive having their power interrupted at any time. You could provide something like a 30-second notification of a power outage, but the instrument shouldn’t be damaged if the notification is missed.
- Instruments should be independent, and not able to take down other systems if they go wrong.
- You need to think about current sensing, in-rush current, fuses, whether the fuses should be resettable, contactors, solid-state switches (be careful, they are easily killed by in-rush current), pre-charging of capacitors, etc.
- For DC hot-swap power supplies, the Texas Instruments TPS2660x is a very nice series of ICs. Up to 55V, 2.23A, with reverse polarity protection, and in-rush current limiting.

Power supplies and capacitors are the most unreliable components

- Some capacitors have surprisingly limited lifetimes (only 1000 hours or so), particularly electrolytics when that are operated close to their maximum ratings (voltage, peak current, temperature).
- Tantalum capacitors can develop shorts and burn up, particularly if operated close to their maximum ratings, or if they are ever even slightly over their maximum voltage, or if the voltage is even slightly negative.
- Ceramic capacitors are highly reliable, but have extremely low ESR that can be a problem.
- Maximum stress on components tends to happen when the power is turned on. So, try to avoid doing this too often, and/or ramp up the current slowly.

Satellite communications

- Iridium OpenPort (128 kbps) has been very successful for Dome A (note: OpenPort has been replaced by Iridium Pilot, which is presumably better).
- However, the Iridium system is by no means reliable, and there are occasional outages that can last for hours.
- It is not possible (to the best of my knowledge) to remotely ssh into an Iridium OpenPort. You have to rely on the supervisor computer in Antarctica initiating the connection to the outside world. This requires careful programming to ensure that it always works.
- The OpenPort units do occasionally hang, and need power-cycling. This can be detected by software.
- At Dome A we also have old-school Iridium modems (2400 baud) that are connected to the supervisor computers using RS232. This gives an additional mechanism to take control remotely, and doesn't require a working LAN. This has proved its worth several times at Dome A.
- We also support sending commands, and receiving responses, via Iridium SBD messages. This can help recover a situation where unexpected failures have occurred.

3km from the South Pole, Jan 2012, M. Ashley