The PoGOLite pathfinder mission for balloon-borne hard X-ray polarimetry

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For the PoGOLite Collaboration

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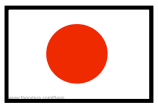
Introduction

- PoGOLite is a balloon-borne hard X-ray polarimeter optimised for compact objects (~25-100 keV)
- First successful balloon flight of reduced area pathfinder polarimeter during summer 2013
- Studied backgrounds (high latitude flight), observed Crab, ... learnt a lot.

The PoGOLite Collaboration

KTH
Stockholm Uni.
DST Control
SSC Esrange

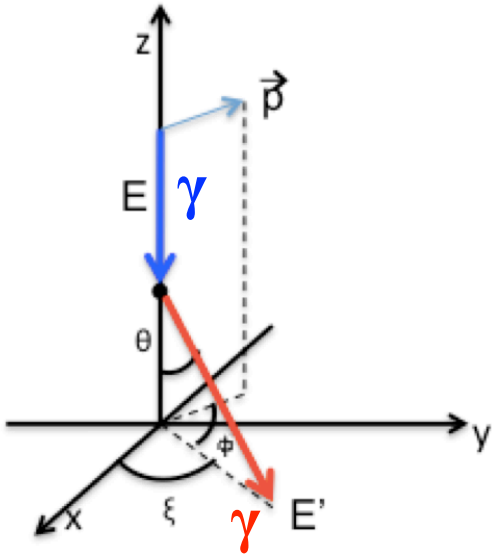


Hiroshima University,
Tokyo Inst. of Tech,
Waseda, Nagoya, ISAS/
JAXA

SLAC KIPAC
Uni. of Hawaii

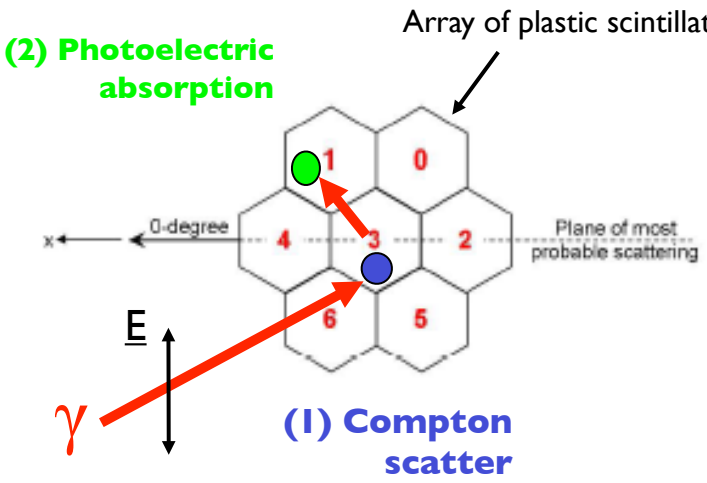
MSU
CAO

Measuring polarisation

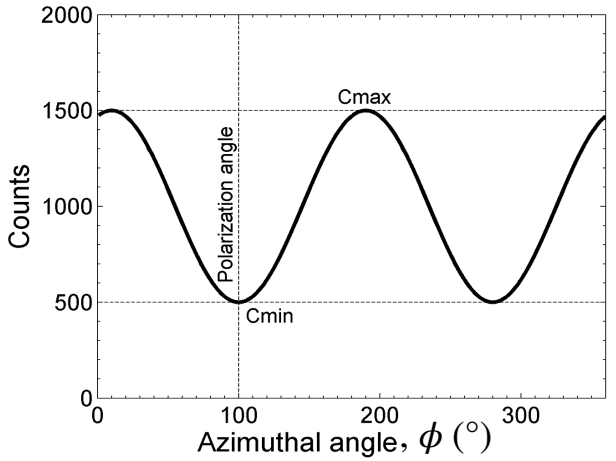


- γ from a **polarised** source undergo **Compton scattering** in segmented detector material
- Higher probability of being **scattered perpendicular** to the **electric field vector**
- Observed **azimuthal scattering angles** are **modulated by polarisation**

$$\frac{d\sigma}{d\Omega} = \frac{r_o^2}{2}\frac{E'^2}{E^2}\left(\frac{E'}{E} + \frac{E}{E'} - 2\sin^2\theta\cos^2\phi\right)$$



Modulation curve

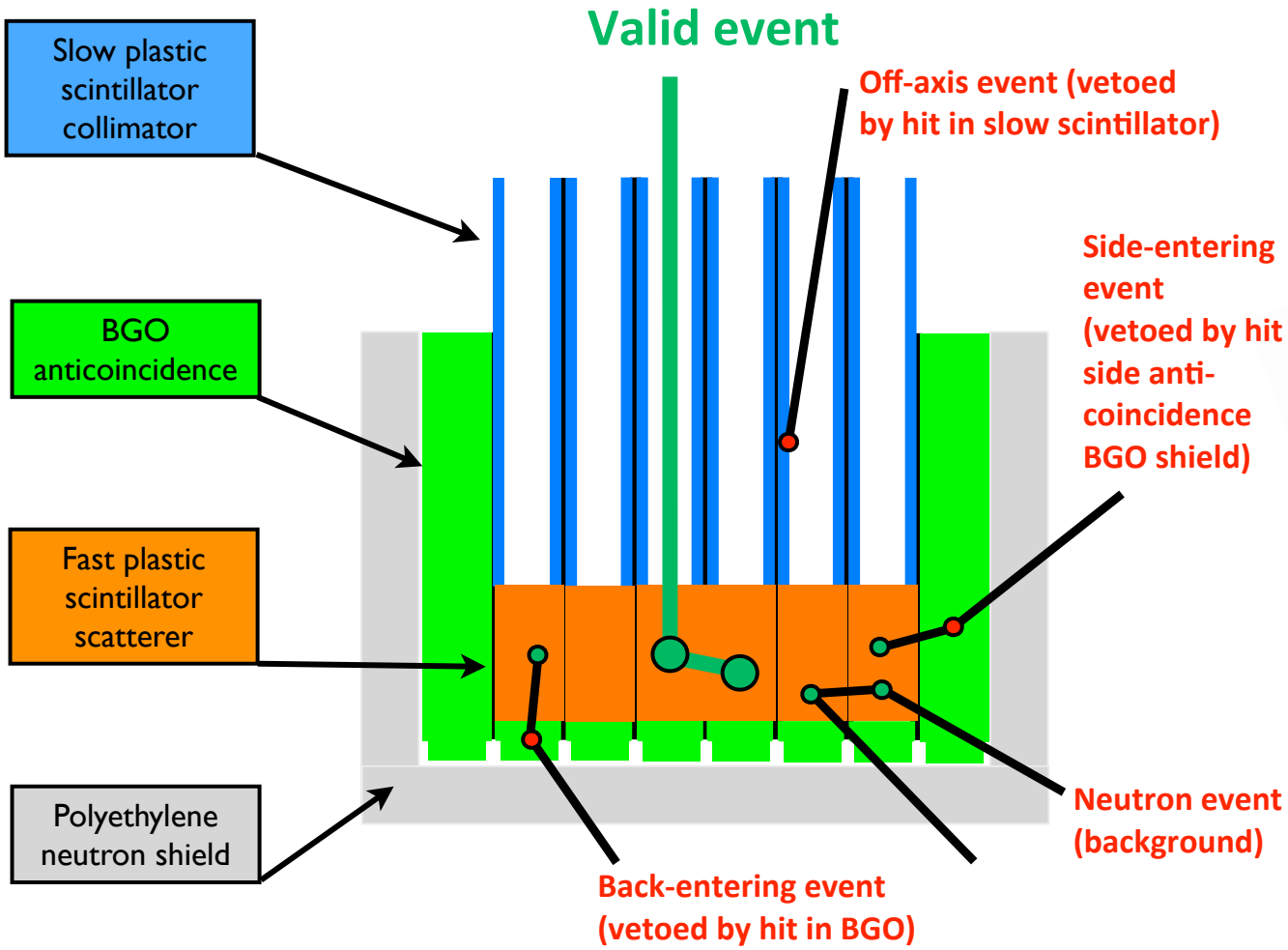


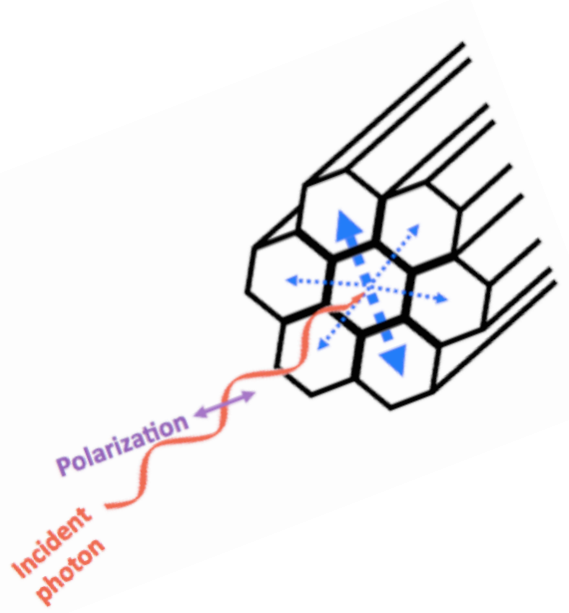
$$\mu = \frac{C_{max} - C_{min}}{C_{max} + C_{min}} \Rightarrow P = \frac{\mu}{\mu_{100}}$$

Modulation factor **Polarization degree**

Principle

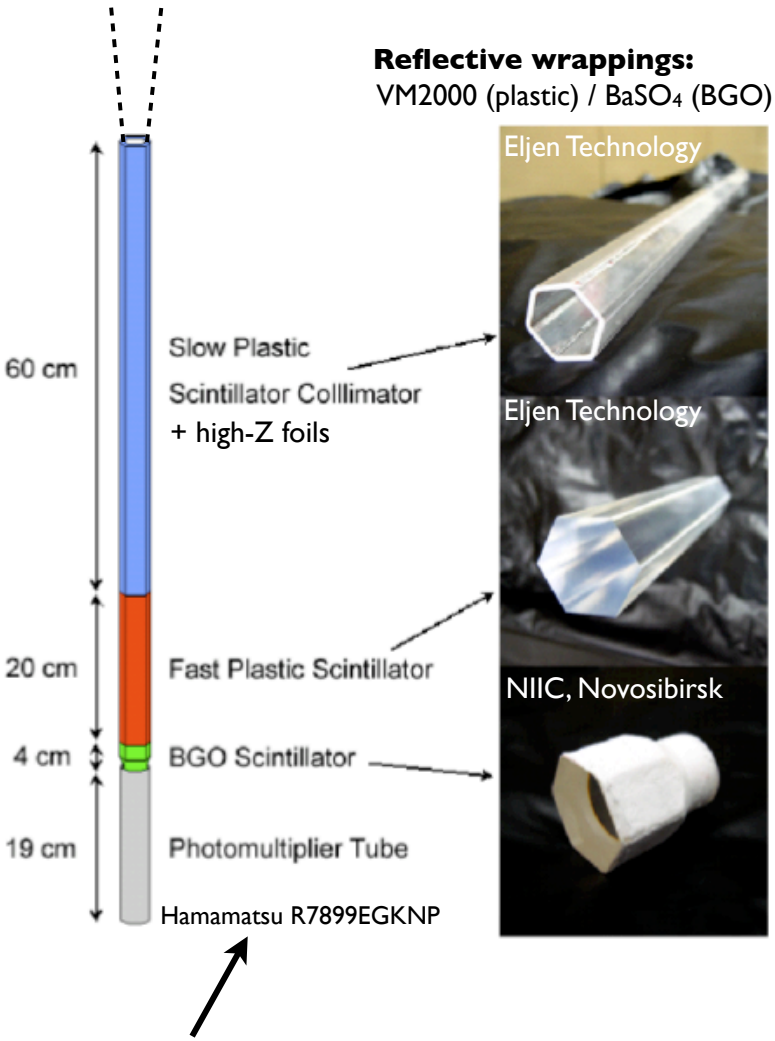
- **Polarised** γ undergo **Compton scattering** in a hexagonal array of plastic scintillators
- Higher probability of being **scattered perpendicular** to the **electric field vector**
- Observed **azimuthal scattering angles** are **modulated by polarisation**





Polarimeter

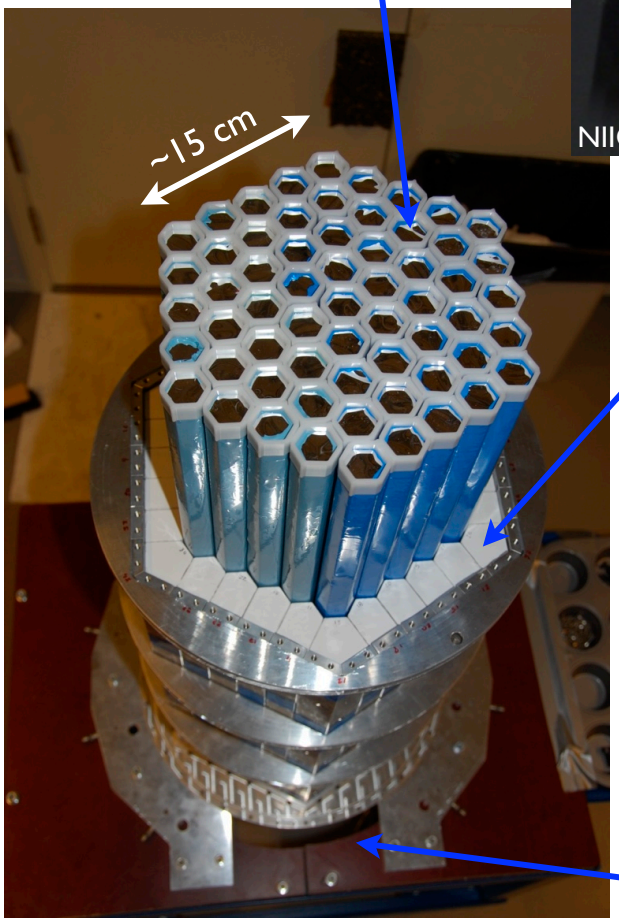
FoV ~$(2.5°)^2$



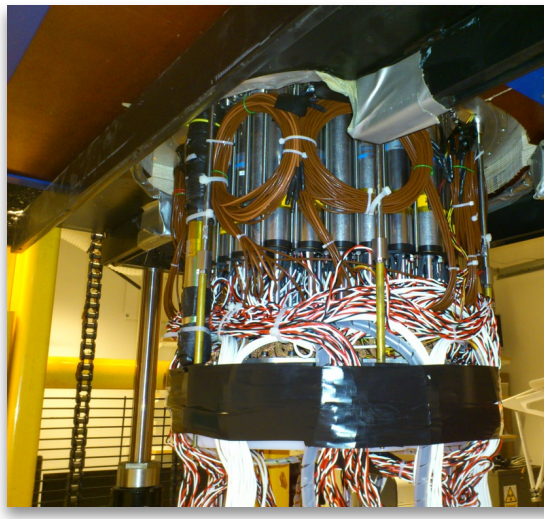
Reflective wrappings:
VM2000 (plastic) / $BaSO_4$ (BGO)

@ 25 keV only 1-3 keV Compton deposited - single p.e. detection
(PMT has 0.05 p.e. ripple @ 10^6 gain)

Phoswich Detector Cells (~30 kg)

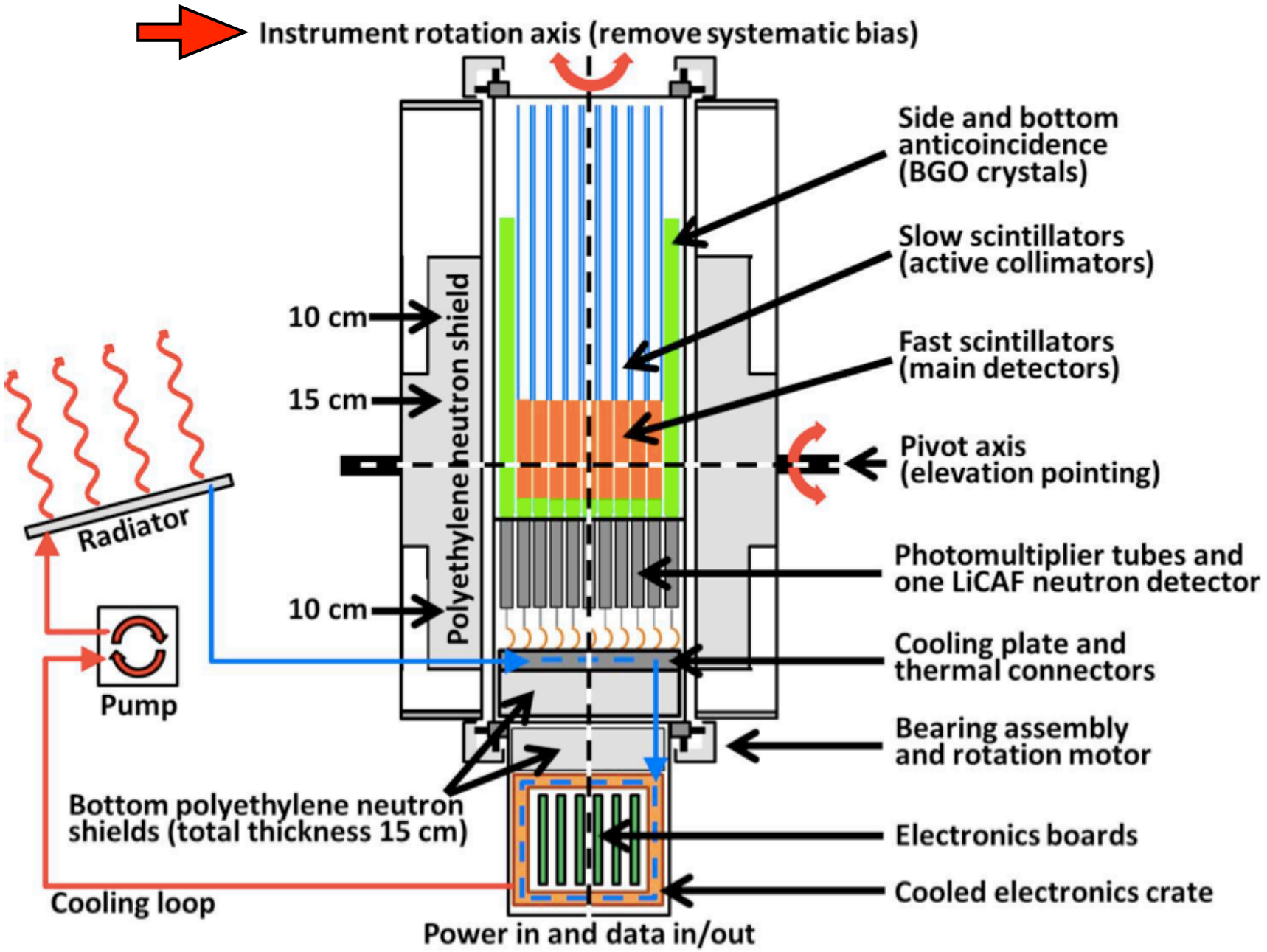


Side anticoincidence, BGO (~150 kg)

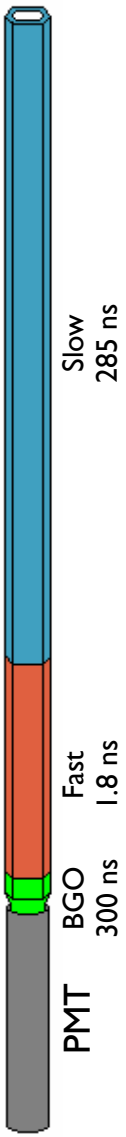


PMTs and cooling system

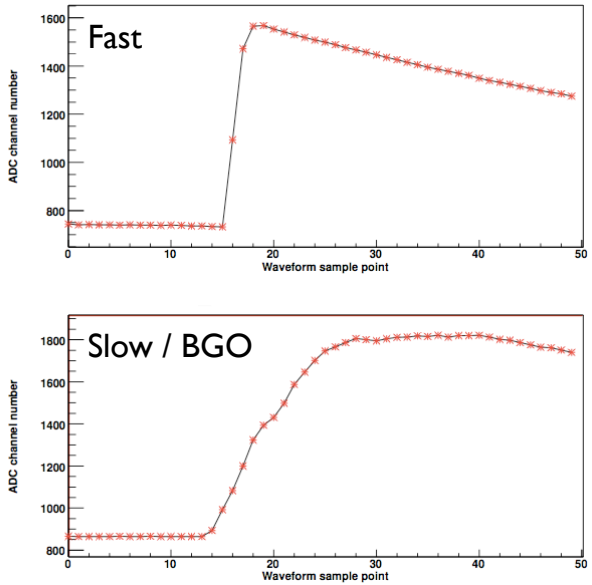
Pathfinder instrument
(61 cells)

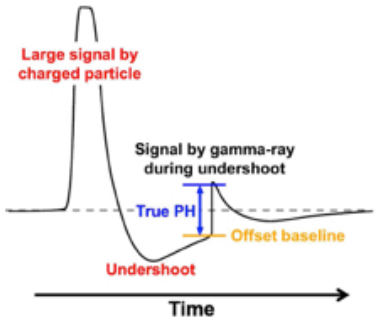

Instrument rotation axis (remove systematic bias)
Side and bottom anticoincidence (BGO crystals)
Slow scintillators (active collimators)
Fast scintillators (main detectors)
Pivot axis (elevation pointing)
Photomultiplier tubes and one LiCAF neutron detector
Cooling plate and thermal connectors
Bearing assembly and rotation motor
Electronics boards
Cooled electronics crate
10 cm
15 cm
10 cm
Polyethylene neutron shield
Radiator
Pump
Bottom polyethylene neutron shields (total thickness 15 cm)
Cooling loop
Power in and data in/out

Data acquisition and event selection

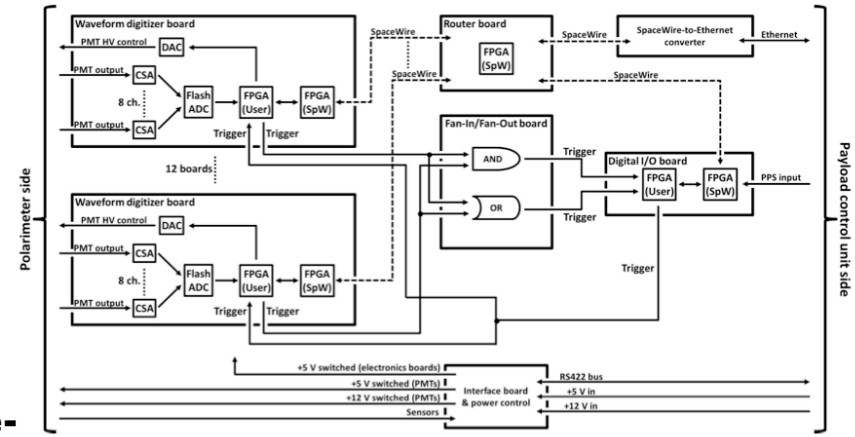


PSD: 12 bit / 37.5 MHz waveform sampling



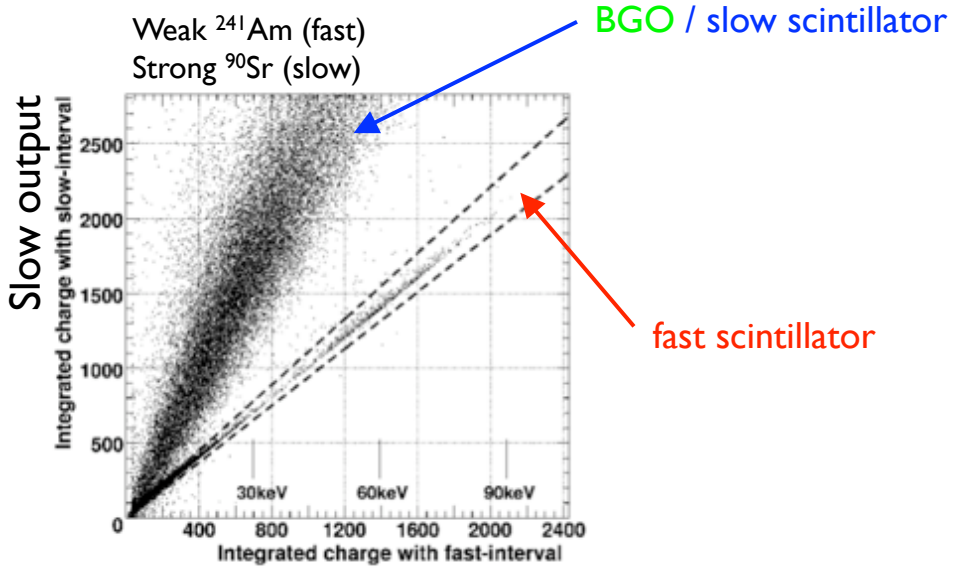


If no UD/PSD veto, **15 pre- and 35 post-trigger samples** are saved



NEC/Shimafuji + JAXA

- Pulse-shape discrimination between signals from fast scintillator and BGO/slow scintillator
- Fast scintillator branch is chosen for analysis



Polarimeter design

Figure of Merit:
Minimum
Detectable
Polarisation (3σ)

Background rate

Small field-of-view: low aperture background.
BGO anticoincidence: low γ + particle backgrounds
Polyethylene shielding: suppresses dominant neutron background

$$MDP_{99\%} = \frac{4.29}{\mu_{100} R_S} \sqrt{\frac{R_S + R_B}{T}}$$

Modulation for 100% polarised source

Geometry

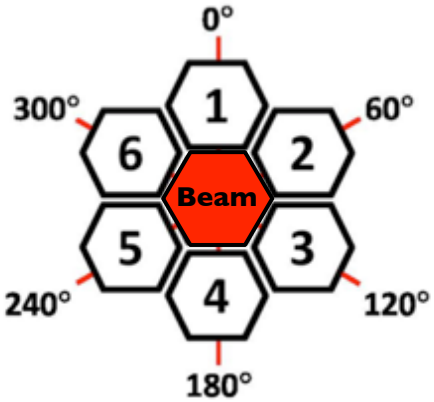
Signal rate

Area, efficiency

Observation time

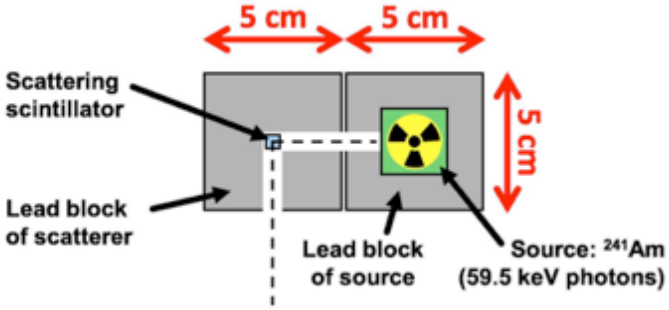
Long duration balloon flight

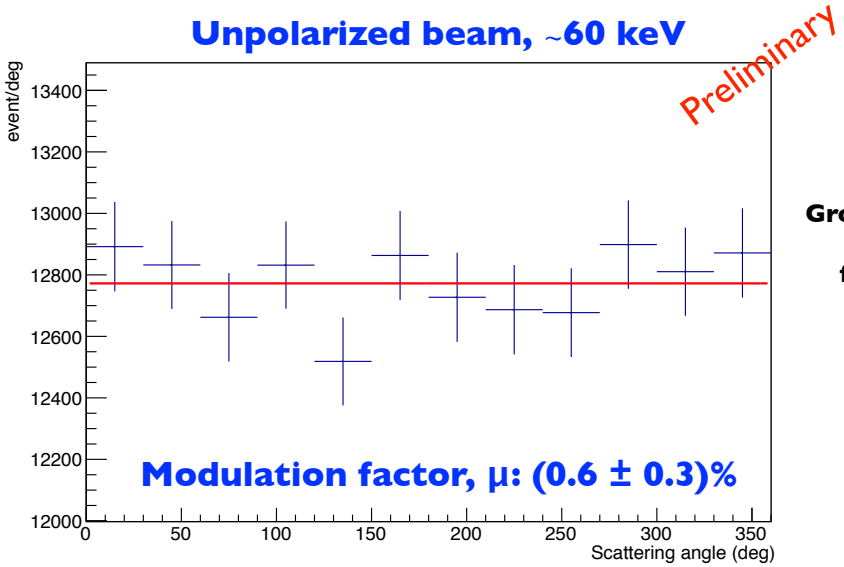
Modulation factor



- Polarisation is a **positive definite** quantity

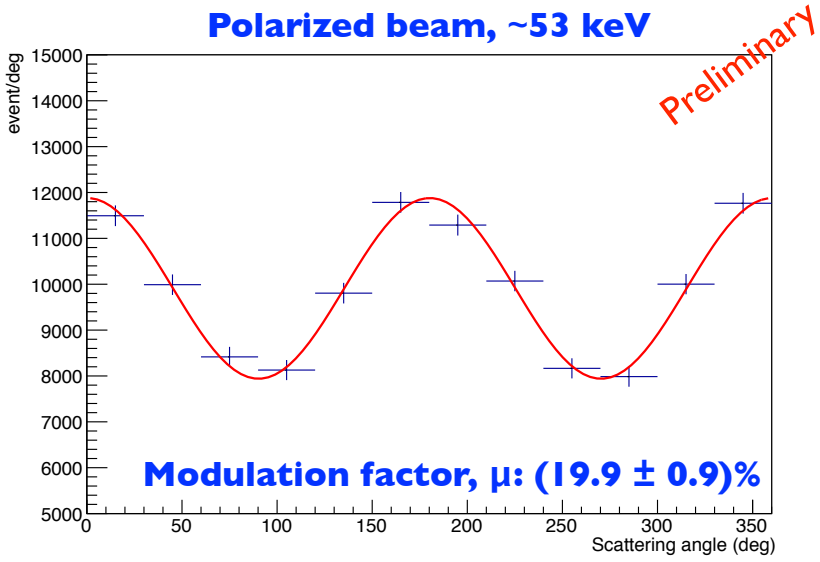
- Important to characterise with both polarised (radioactive source and synchrotron) and unpolarised beams



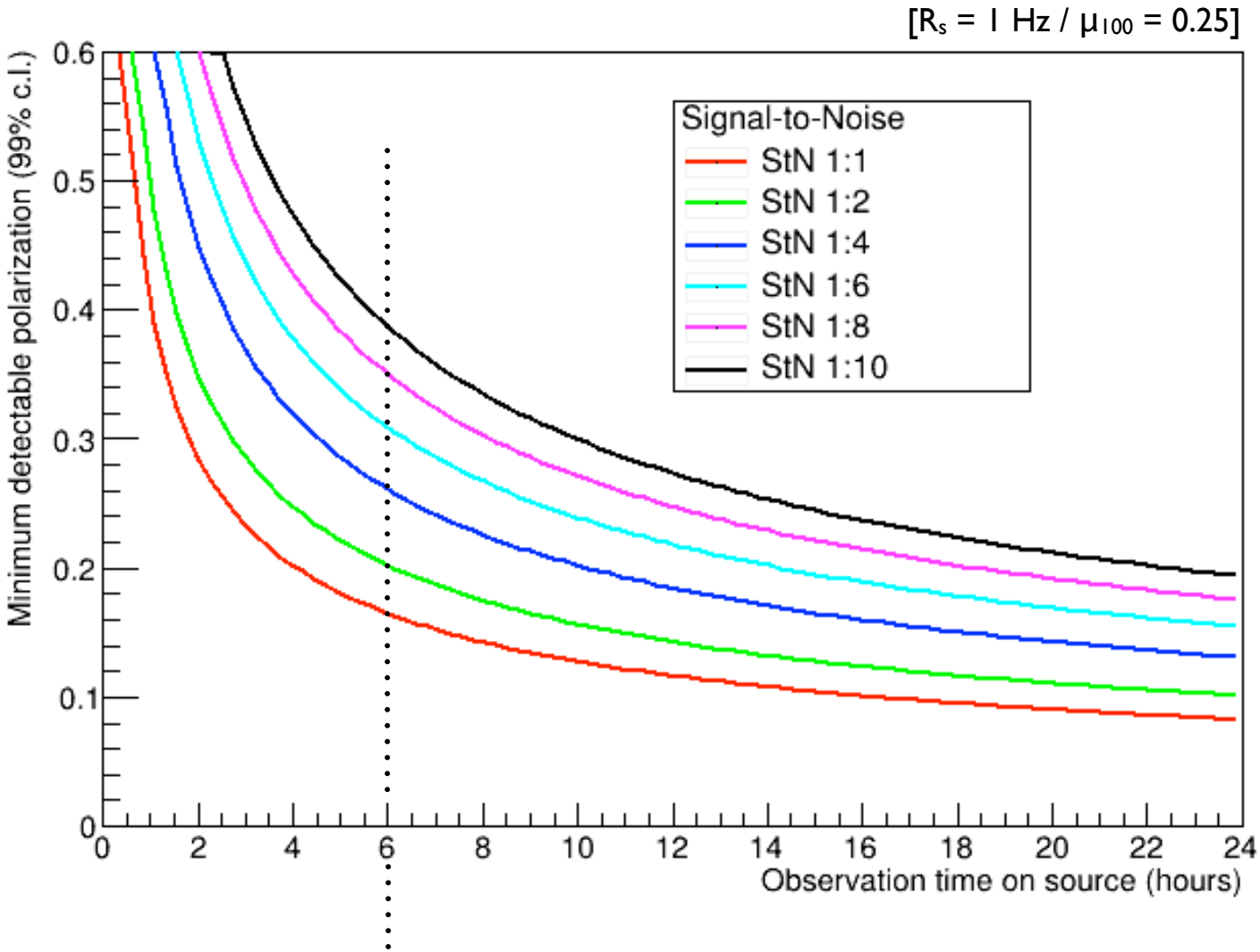


Ground calibration using flight analysis

2 hit only

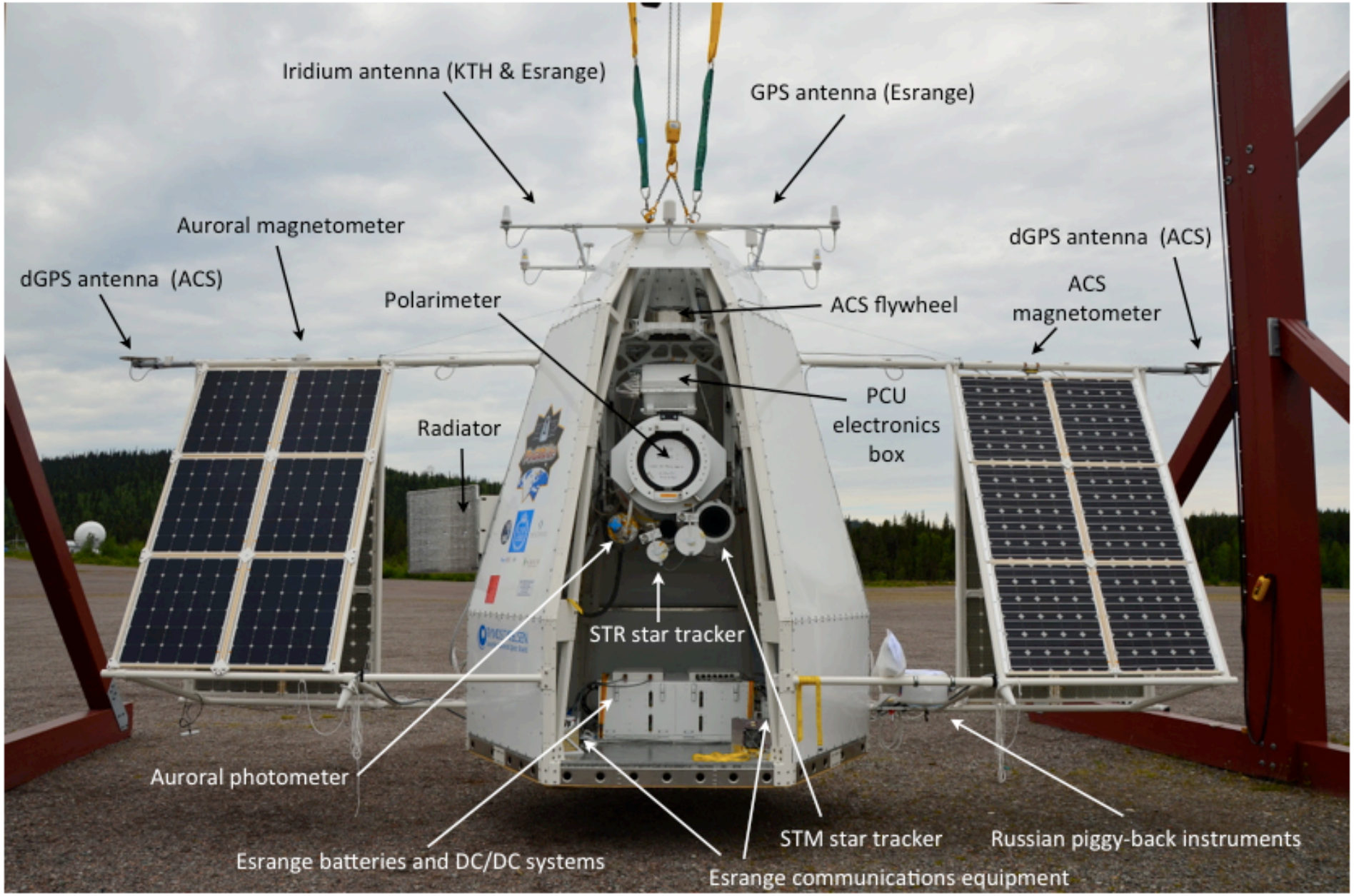


MDP


[R_s = 1 Hz / μ_{100} = 0.25]
Minimum detectable polarization (99% c.l.)
0.6
0.5
0.4
0.3
0.2
0.1
0
Signal-to-Noise
StN 1:1
StN 1:2
StN 1:4
StN 1:6
StN 1:8
StN 1:10
0
2
4
6
8
10
12
14
16
18
20
22
24
Observation time on source (hours)

e.g. 21.6 ks

The PoGOLite pathfinder gondola



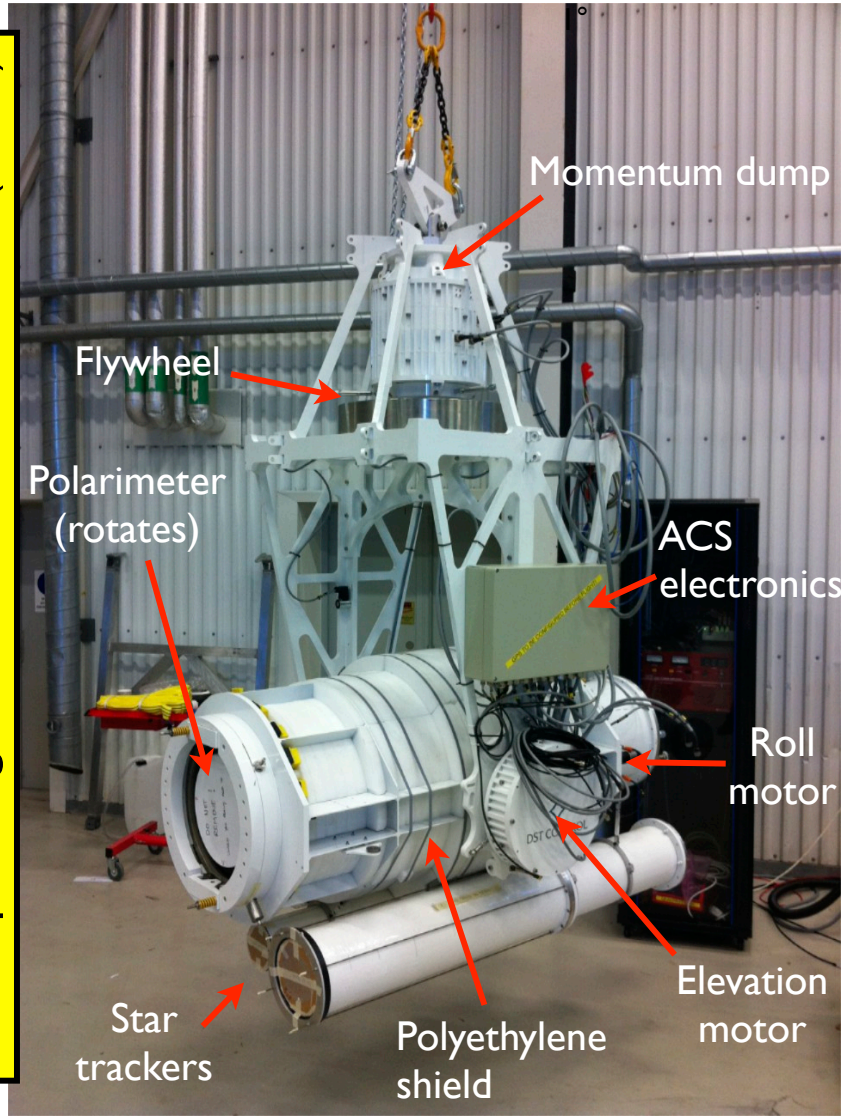
~1750 kg (no ballast); science systems: ~300 W; gondola systems: ~200 W

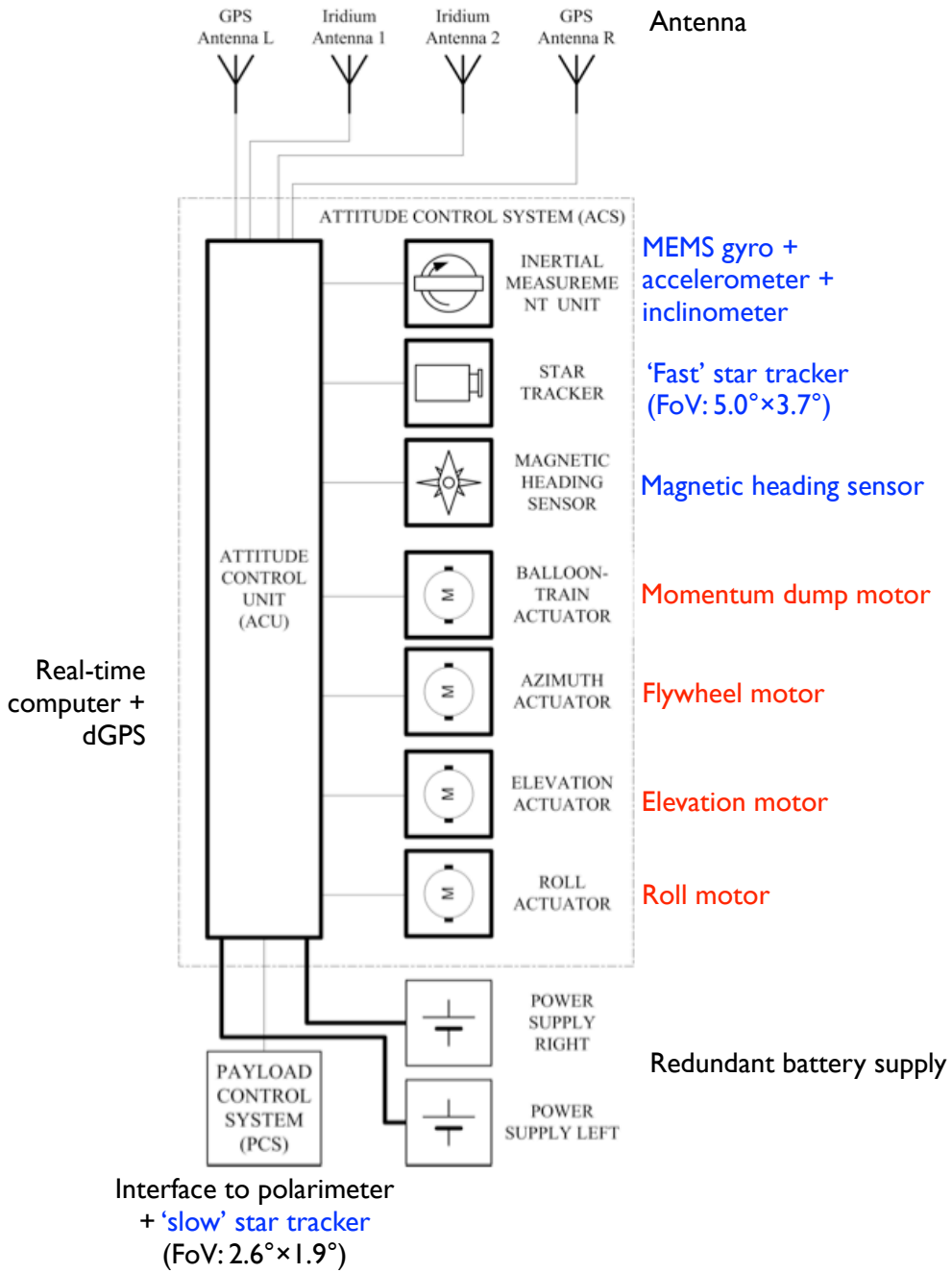
DST CONTROL

Attitude control

ITAR free!

Aim: pointing to better than 5% of FoV (~0.1°)





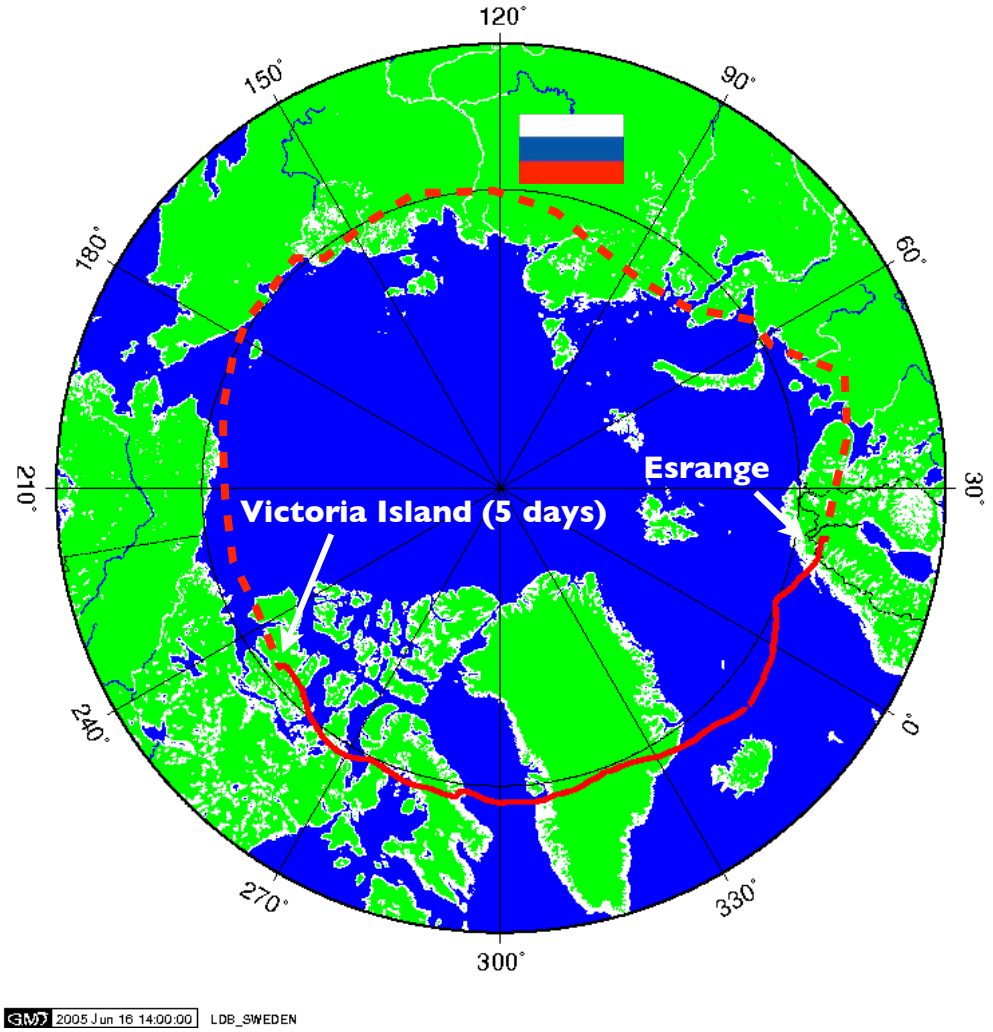
The rocky road to flight

- **2010:** 'turn-around' flight in August (~1 day). Cancelled (NASA embargo).

- **2011:** circumpolar flight (~15 days) proposed
  - Russian overfly permissions not secured in time
  - ~5 day flight to Canada adopted
  - Balloon damaged during launch. Mission terminated after a few hours.

- **2012:** circumpolar flight proposed
  - Poor weather conditions prevent launch

- **2013:** circumpolar flight successful



Circumpolar challenges

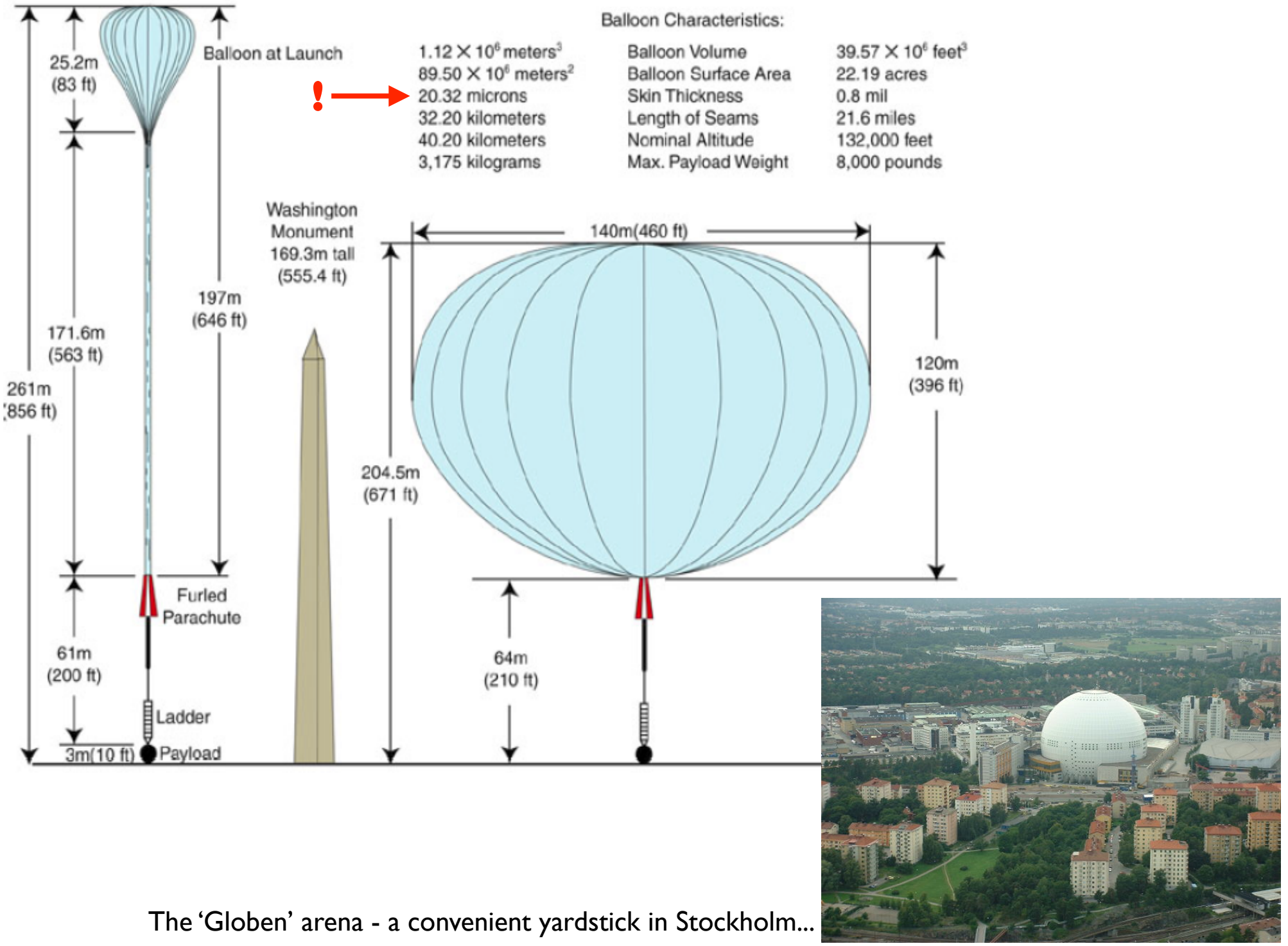
- No line-of-sight communications (Ethernet over radio). Low bandwidth Iridium over-the-horizon .
- Robust data storage
- Autonomy
- Reliance on solar cells

Pathfinder flight goals

- To test instrument design, attitude control system and ancillary systems
- To measure backgrounds and study rejection techniques
- To observe Crab, Cygnus X-1 (if in hard state)
- To learn how to conduct circumpolar balloon flights from the Esrange Space Centre in collaboration with Russian colleagues

Esrange Space Centre

67° 53’ N, 21° 04’ E



The 'Globen' arena - a convenient yardstick in Stockholm...

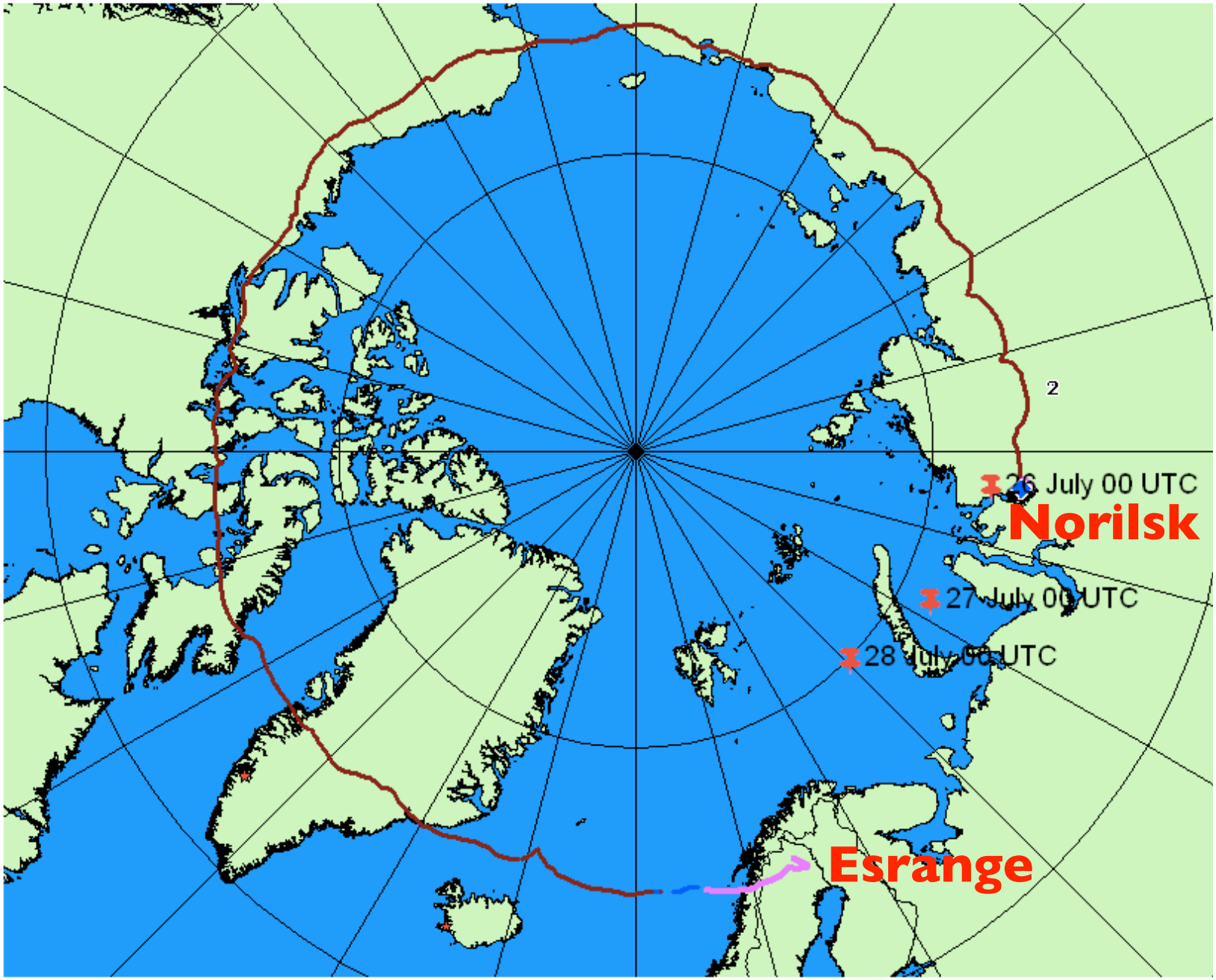

HERCULES
VOLVO

Launch / 2013-07-12 / 0818 UT

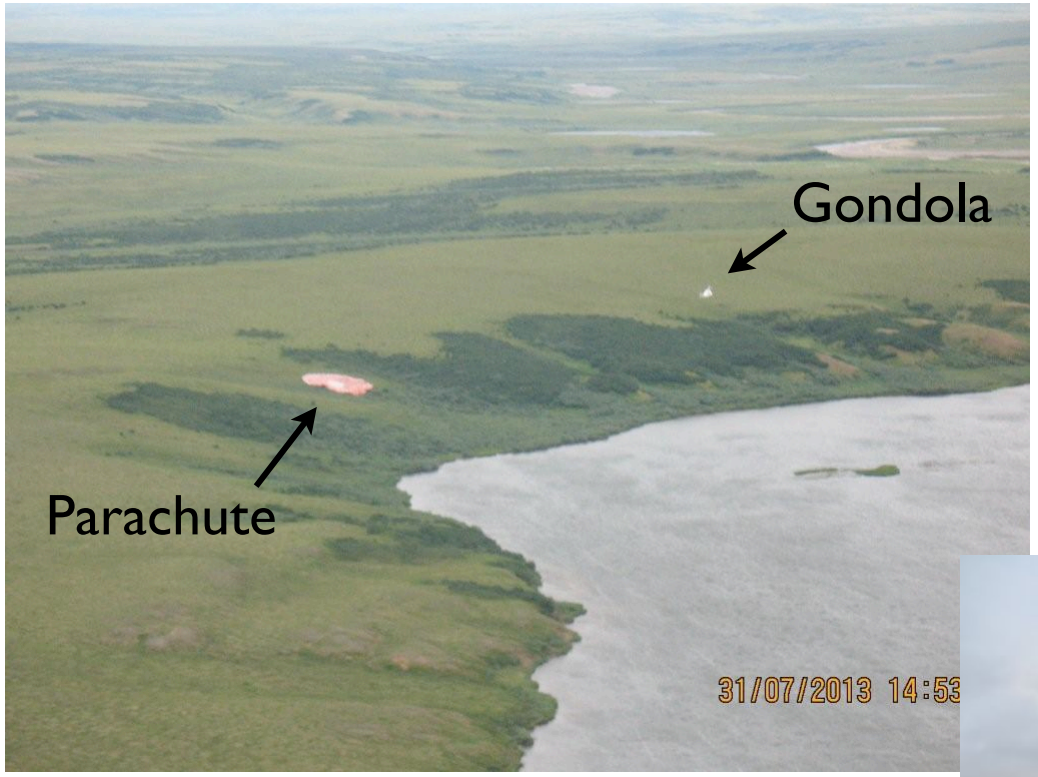
Launch
2013-07-12
0818 UT

Cut
2013-07-25
2324 UT

Landing
2013-07-26
0015 UT



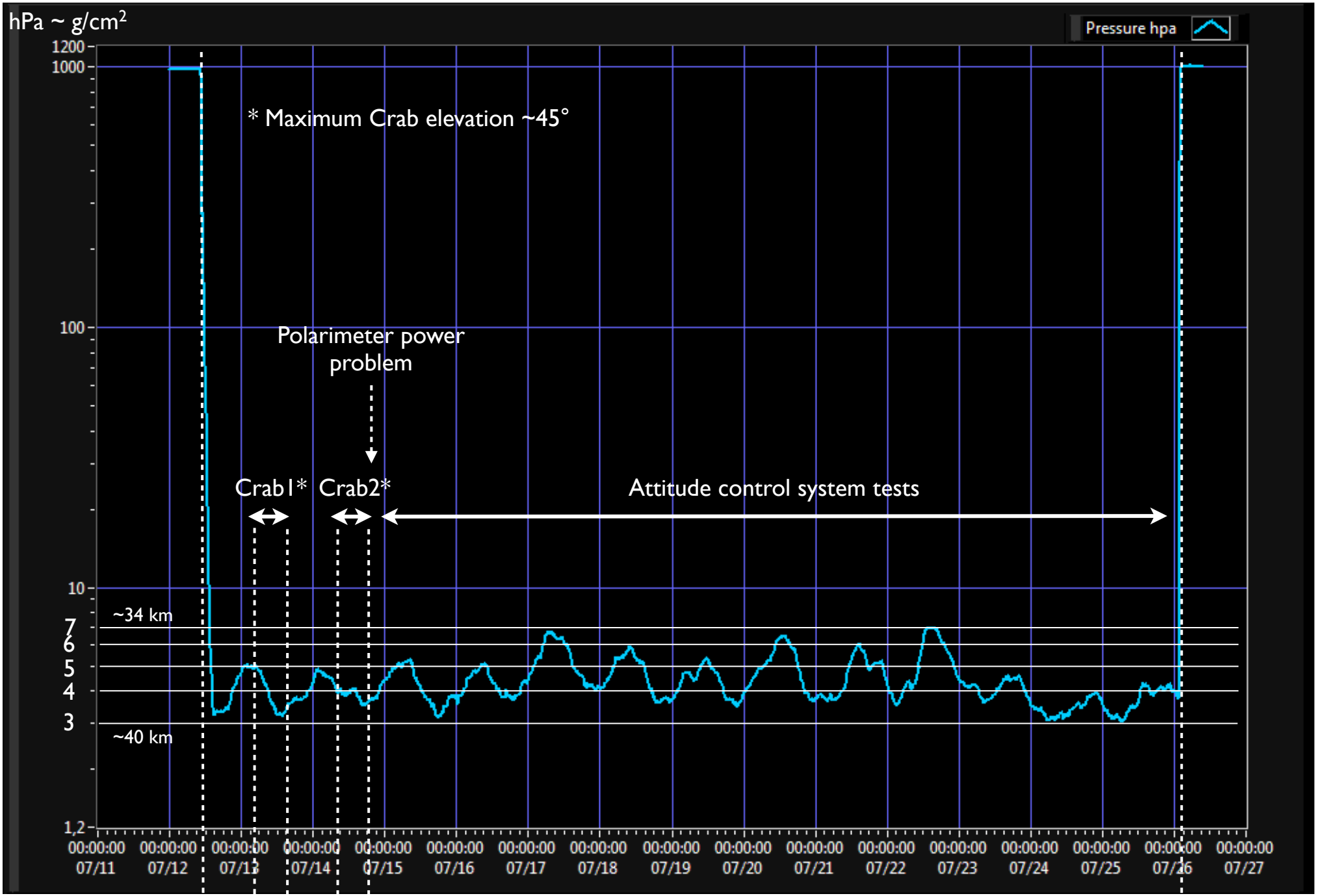
Landing on the Siberian tundra



Courtesy of David Shifrin, CAO

Payload recovery

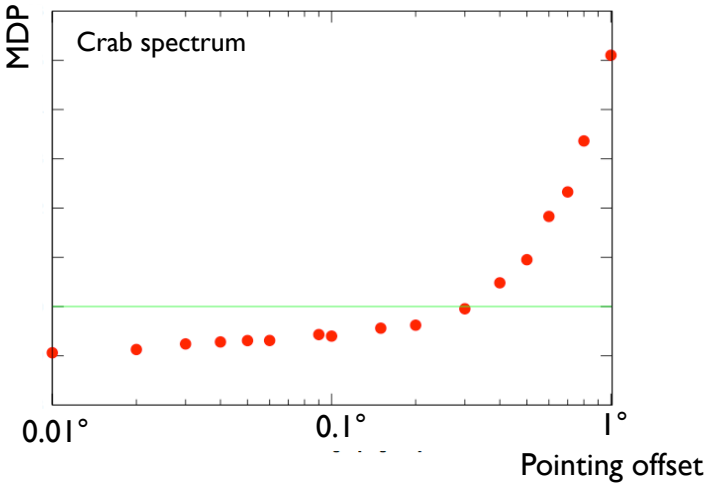
- Science observations conducted over low bandwidth Iridium links
- Data stored on-board the gondola ⇒ disks needed to be returned to KTH

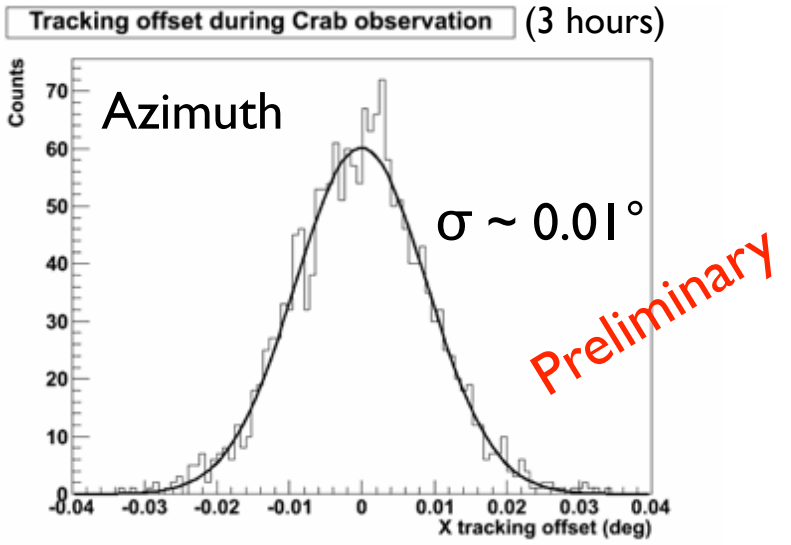


Launch ~13.5 days Cut

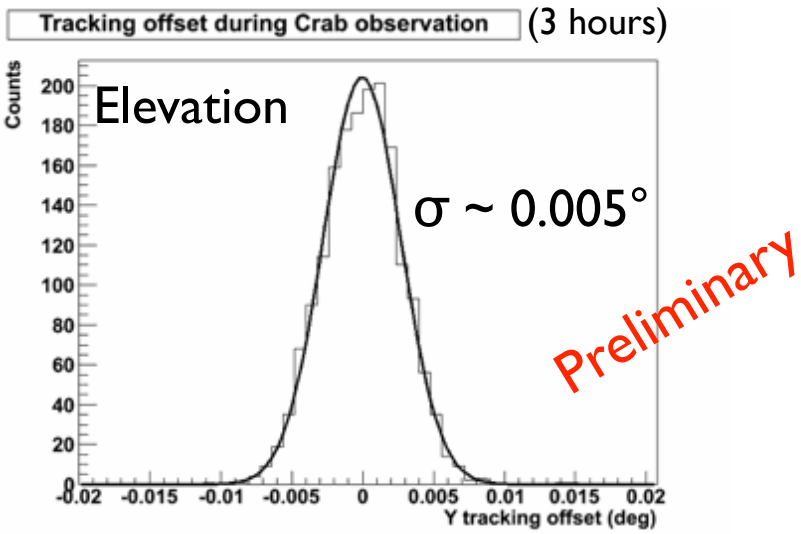
Attitude control system performance

- Goal: to point within 0.1° (~5% of FoV)

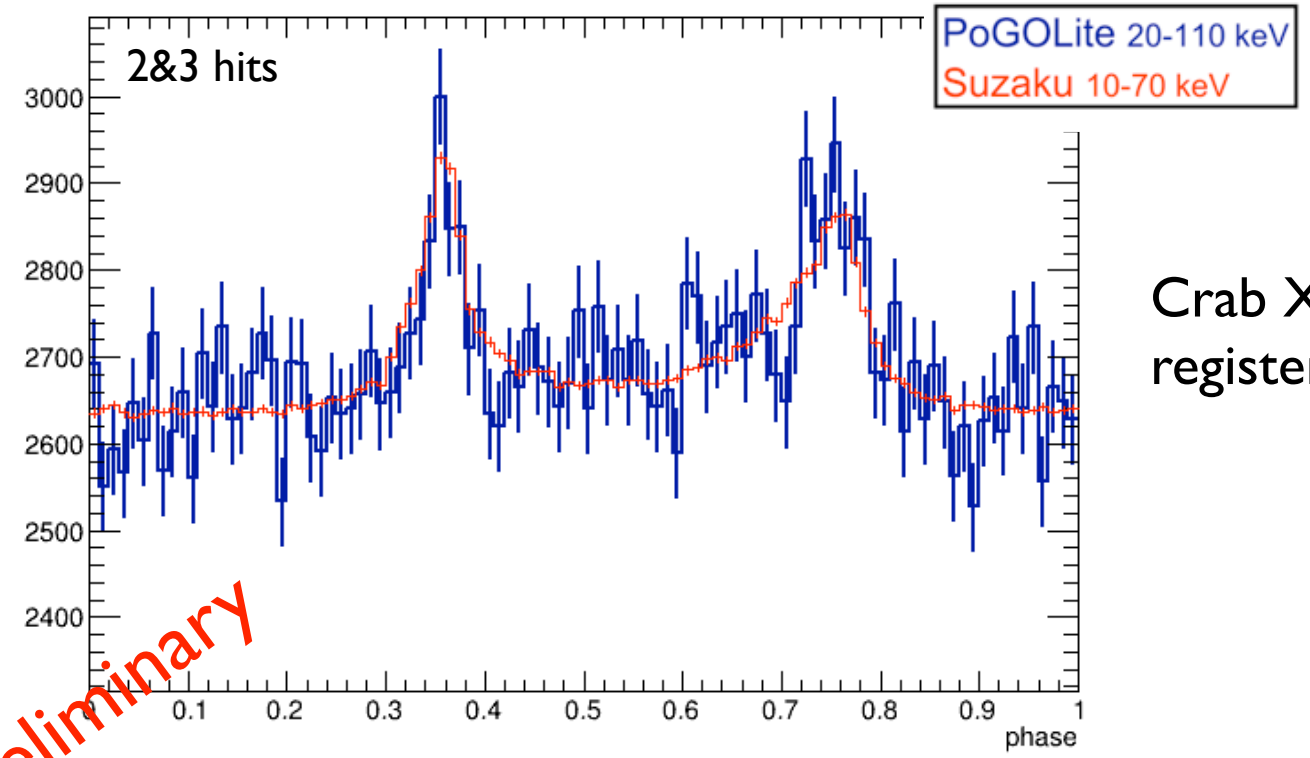




- Absolute pointing with differential GPS / magnetometer
- Relative pointing with MEMS gyros
- Once on target, track on a nearby star
- Challenging since Crab is close (~25°) to the sun
- Excellent performance observed



Crab light curve

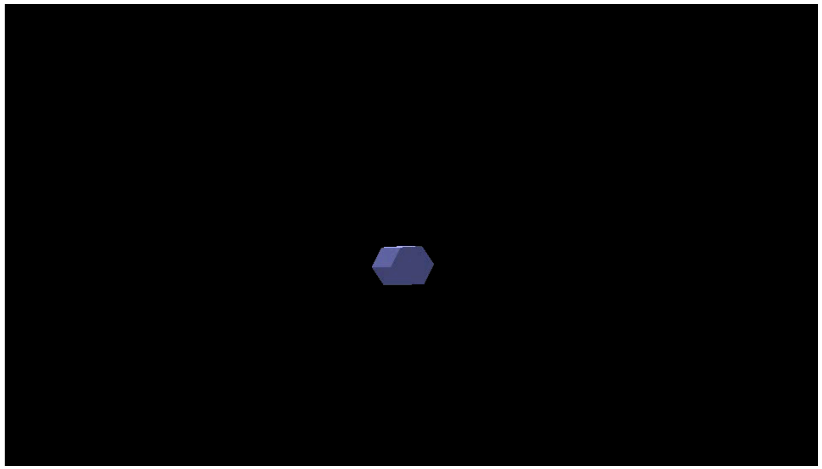


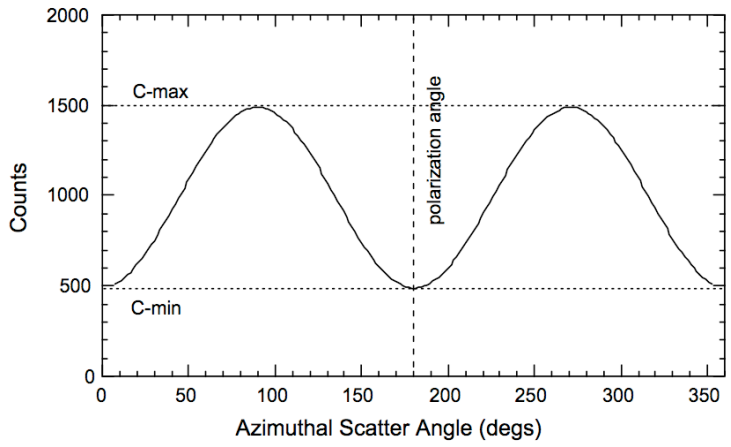
Crab X-rays are registered by polarimeter

- Using Suzaku light curve with flat background as a template
  - 2 hit signal : background ~ 1:7

Backgrounds

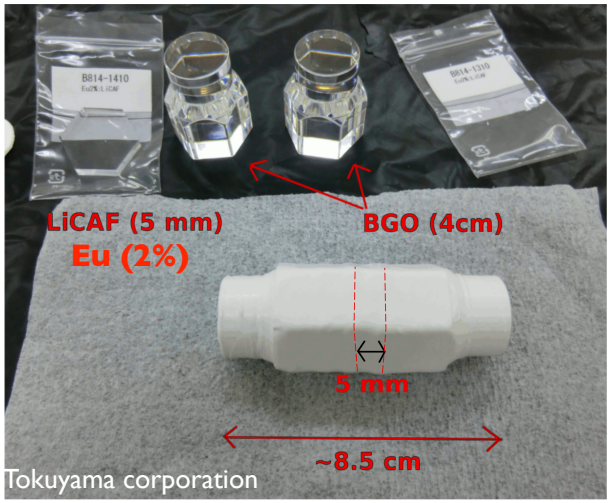
- **'Signal':** two coincident fast scintillator energy deposits, no activity in lateral anticoincidence
- Can be faked by **background** processes: atmospheric neutrons, atmospheric X/γ-rays, galactic X/γ-rays, charged cosmic-rays
- Relatively high latitude balloon flight
- Backgrounds mitigated by restricted FoV, BGO anticoincidence, polyethylene shield, analysis selections. What remains:
  - Atmospheric neutrons scattering from the polyethylene shield into the polarimeter (dominant)
  - High energy (> 100 keV) atmospheric X/gamma-rays
- Both backgrounds will degrade the MDP; any anisotropy may also generate features in the modulation curve - very important to understand.

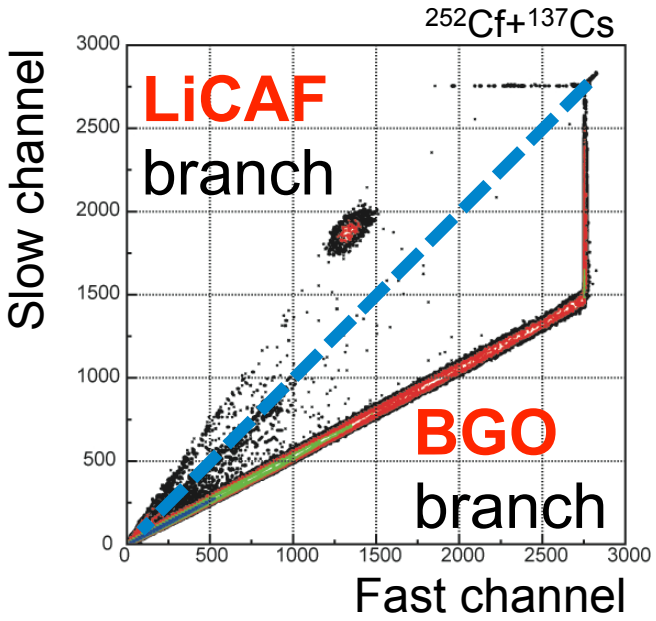




Neutron background

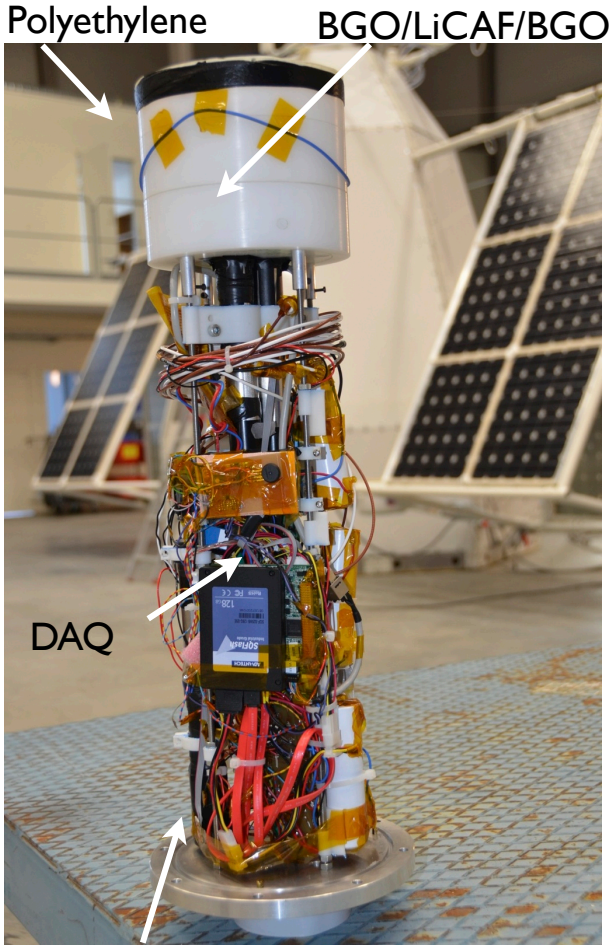
- Neutron background is found to dominate (Geant4 simulations)
- Neutrons are moderated by a ~15 cm thick **polyethylene shield** (reduces background by factor 10)
- 0.5 MeV < E_n < 500 MeV
- Scattering in polyethylene results in a isotropic background





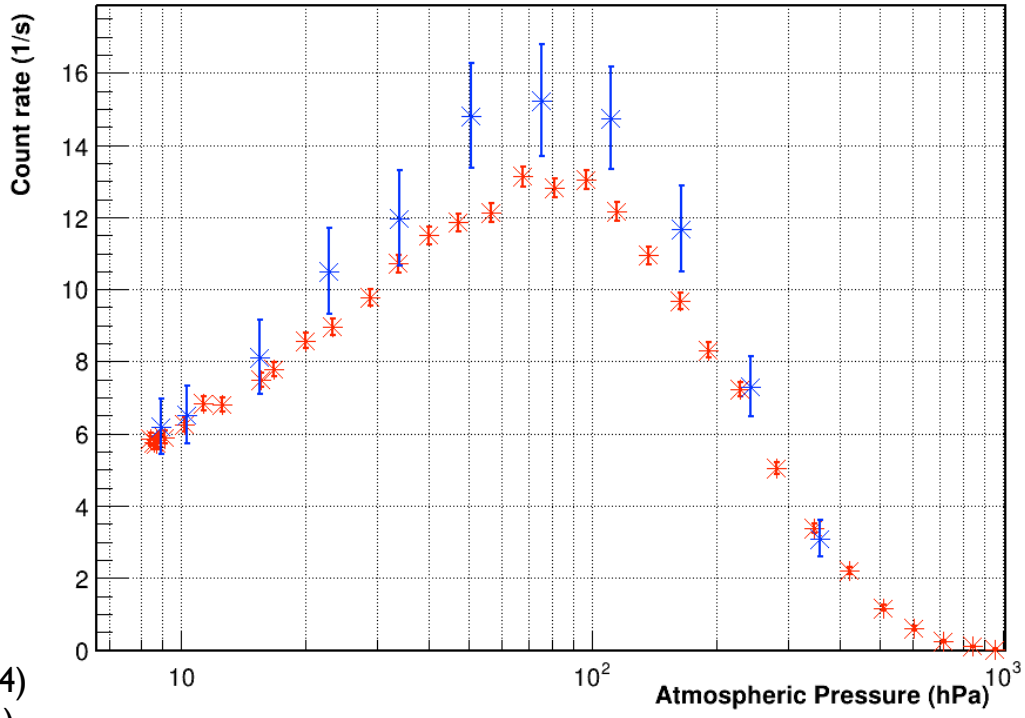
- Neutrons monitored during flight by a novel $LiCaAlF_6$ ('LiCAF') detector in a Phoswich arrangement with BGO
- $n+^6Li \rightarrow T+\alpha$ (MeV line), 9000 γ/n, τ~1.5μs (BGO ~0.3μs)

PoGOLino



PoGOLino

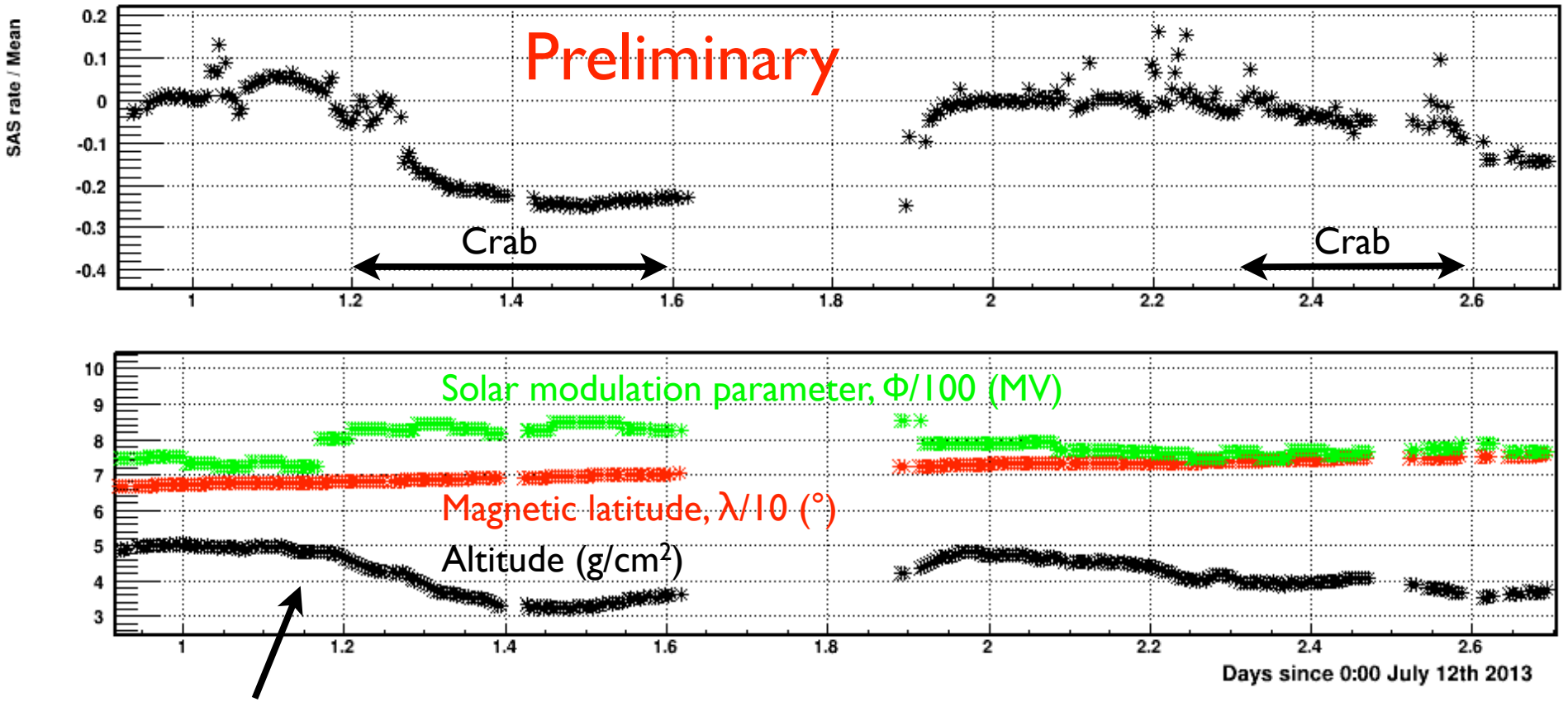
- Results from the PoGOLino flight used to validate PLANETOCOSMICS (Geant4)-based predictions for atmospheric neutron spectra at high latitudes



Instrument: M. Kole et al., submitted to Nucl. Instr. Meth. A (2014)
Modeling: M. Kole et al., submitted to Astroparticle Physics (2014)

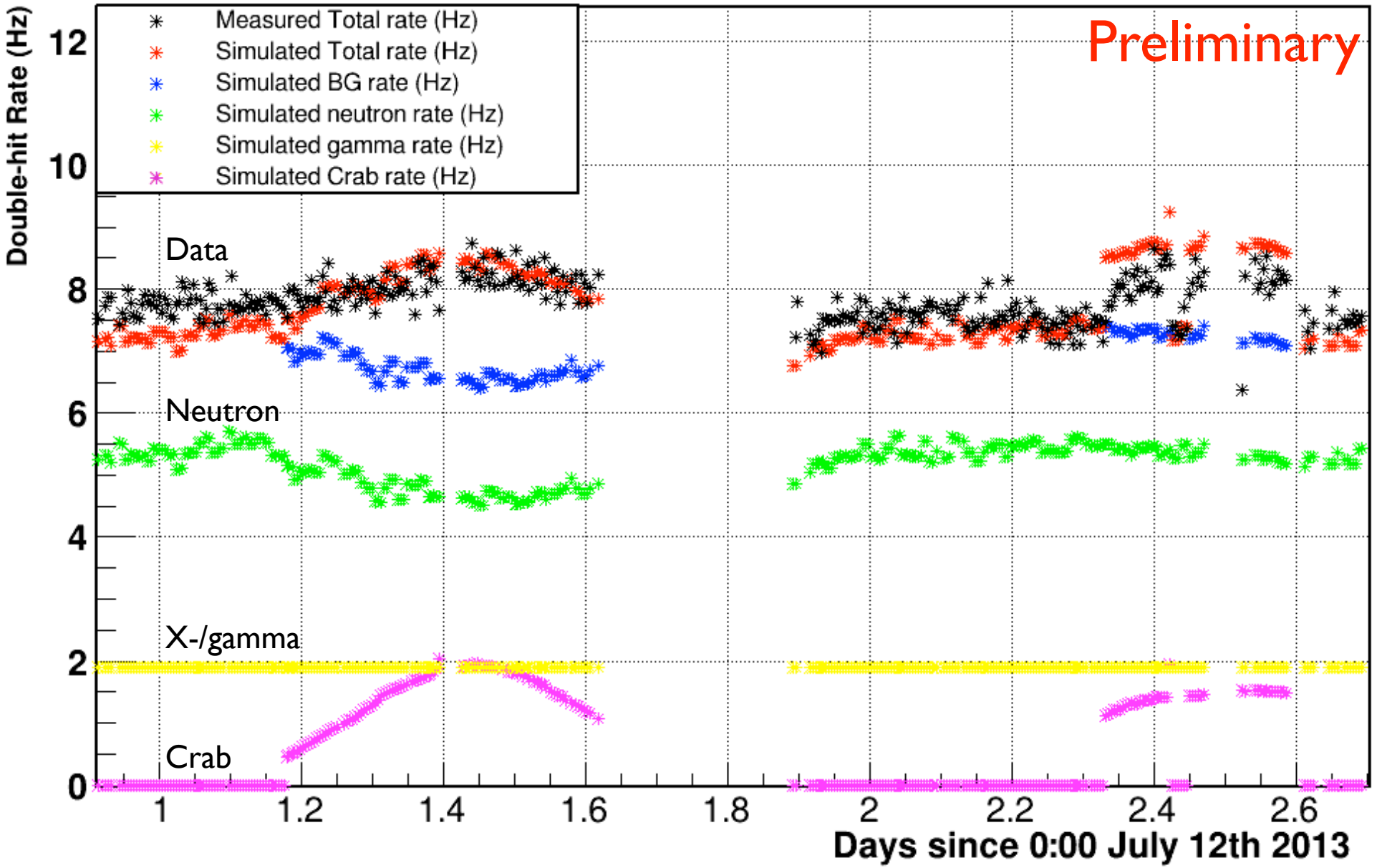
PoGOLite background rates

Side anticoincidence rate (mean subtracted, corrected for temperature, elevation)



Time dependence of dominant neutron background is modeled based on these 3 inputs

Background components

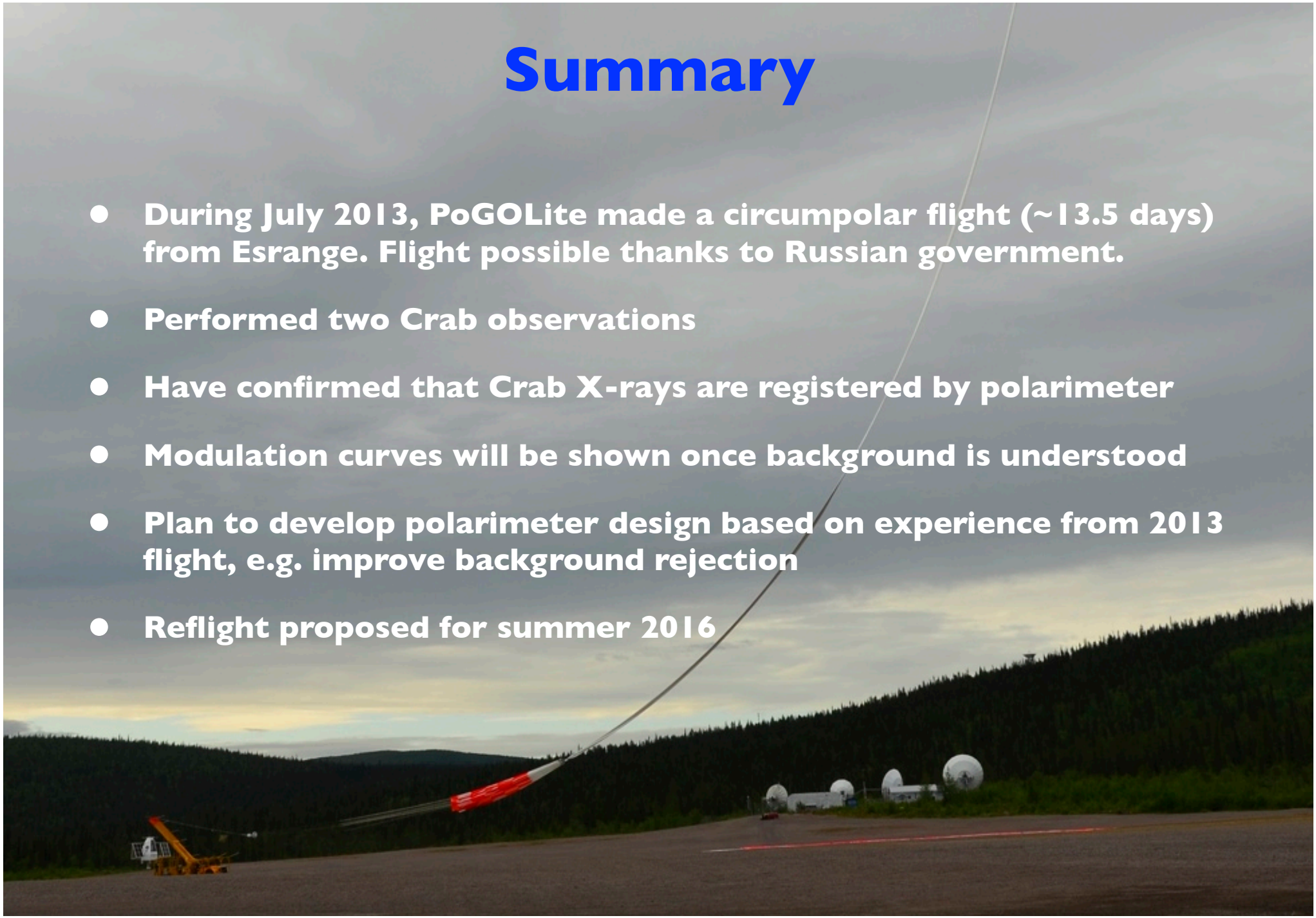


Outlook

- Continue to develop / test background model
- Understand possible background contributions to modulation curves
- Polarisation results!

Summary

- During July 2013, PoGOLite made a circumpolar flight (~13.5 days) from Esrange. Flight possible thanks to Russian government.
- Performed two Crab observations
- Have confirmed that Crab X-rays are registered by polarimeter
- Modulation curves will be shown once background is understood
- Plan to develop polarimeter design based on experience from 2013 flight, e.g. improve background rejection
- Reflight proposed for summer 2016



RYMDSTYRELSEN Swedish National Space Board
Knut och Alice Wallenbergs Stiftelse
Vetenskapsrådet