



# Experiences From the Early Evolution of the Lithium-ion Space Battery Sector

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# Lithium-ion Infusion



Total Batteries	Mission Name	Orbit / Type	Launch Date	Module Size	Status	Total Batteries	Mission Name	Orbit / Type	Launch Date	Module Size	Status	Total Batteries	Mission Name	Orbit / Type	Launch Date	Module Size	Status	
1	STRV-1D	GTO	15 Nov 2000	6s 1p	Launched	47	COSMO-3	LEO	25 Oct 2008		Launched	80	SSOT	LEO	31 Mar 2010	8 10	Delivered	
2	PROBA	LEO	22 Oct 2001	6s 6p	Launched	48	Spirale	GTO	12 Feb 2009	8s 10p	Launched	81	SAC-D	LEO	31 May 2010	8 20	Delivered	
3	Beagle 2	Lander	2 Jun 2003	6s 9p	Launched	49	Kepler	LEO	7 Mar 2009	8s 16p	Launched	82	MARES	ISS	30 Jul 2010	80 2	Delivered	
4	Mars Express	I/P	2 Jun 2003	6s 16p	Launched	50	GOCE	LEO	17 Mar 2009	8s 52p	Launched	84	ALSAT-2	LEO	31 Aug 2010	8 10	Delivered	
5	SCISAT/ACE	LEO	13 Aug 2003		Launched	51	Unnammed	LEO		10s 30p	Launched	85	X-Sat	LEO	30 Oct 2010	7 3	Delivered	
6	Rosetta	I/P	2 Mar 2004	6s 11p	Launched	52	Herschel	L2	14 May 2009	6s 24p	Launched	86	MicroSCOPE	LEO	31 Dec 2010	8 10	Delivered	
7	Philae	Lander	2 Mar 2004	2s 7p	Launched	53	Planck	L2	14 May 2009	6s 24p	Launched	87	Aeolus	LEO	31 Oct 2010	12 28	Delivered	
8	SaudiSat2	LEO	29 Jun 2004	2s 4p	Launched	54	TacSat3 / 3a	LEO	19 May 2009	8s 16p	Launched	88	VNIIEM	LEO	31 Dec 2010	8 52	Delivered	
9	Demeter	LEO	29 Jun 2004	8s 10p	Launched	55	LRO	LLO	18 Jun 2009	8s 84p	Launched	89	MTS (US)	LEO		8 10	Delivered	
10	NSat	LEO	18 Dec 2004	6s 2p	Launched	56	LCROSS	LLO	18 Jun 2009	8s 16p	Launched	90	MMP-1	LEO	31 Jul 2012	8 10	Delivered	
14	Essaim I, II, III & IV	LEO	18 Dec 2004	8s 10p	Launched	57	Deimos-1	LEO	29 Jul 2009	8s 10p	Launched	91	MMP-2	LEO	31 Jul 2012	8 10	Delivered	
15	Parasol	LEO	18 Dec 2004	8s 10p	Launched	58	UK-DMC 2	LEO	29 Jul 2009	8s 10p	Launched	92	GAIA	L2	31 Dec 2011	6 48	Delivered	
16	CryoSat-1	LEO	8 Oct 2005	8s 44p	Launched		KSLV-1	LV	25 Aug 2009	8s 1p	Launched	93	Talisat 7	LEO	31 Dec 2010	10 30	Delivered	
17	Venus Express	I/P	9 Nov 2005	6s 16p	Launched	59	KSLV-1	LV	25 Aug 2009	8s 3p	Launched	96	SWARM	LEO	31 Jul 2010	8 32	Delivered	
18	GIOVE-A	MEO	28 Dec 2005	9s 10p	Launched		KSLV-1	LV	25 Aug 2009	8s 10p	Launched	98	8s10p's	LEO		8 10	Delivered	
21	ST5 A, B & C	GTO	22 Mar 2006	6s 2p	Launched		KSLV-1	LV	25 Aug 2009	84s 2p	Launched		NanoSat		31 Dec 2009	2 2	Delivered	
22	SAR-Lupe 1	LEO	19 Dec 2006	8s 44p	Launched	60	Sumbandila (ZaSat)	LEO	17 Sep 2009	7s 3p	Launched	99	GIOVE-A2	MEO	31 Dec 2009	9 10	On Hold	
27	THEMIS	LEO	17 Feb 2007	8s 8p	Launched	61	TanDEM-X	LEO	30 Nov 2009	12s 24p	Delivered	100	Venus	LEO	30 Jun 2010	10 20	In build	
28	STPSat 1	LEO	9 Mar 2007		Launched	63	TaliSat 5	LEO	31 Dec 2009	10 30	Delivered	101	ExoMars Rover	Rover	30 Jun 2013	9 12	In build	
29	CFESat	LEO	9 Mar 2007	8s 10p	Launched	64	SDO	GEO	3 Feb 2010	8 104	Delivered	102	USG	GEO		8 10	Delivered	
30	SaudiSat3	LEO	17 Apr 2007	4s 6p	Launched	65	CryoSat-2	LEO	28 Feb 2010	8 52	Delivered	103	Sentinel-1	LEO	30 Nov 2011	16 16	In build	
31	COSMO-1	LEO	8 Jun 2007		Launched	66	COSMO-4	LEO	28 Feb 2010		Delivered	104	EMU (US)	Suit			In build	
32	TerraSAR-X	LEO	15 Jun 2007	12s 24p	Launched	67	Picard	LEO	28 Feb 2010	8 10	Delivered	105	Sentinel-3	LEO	30 Nov 2012	9 56	In build	
33	SAR-Lupe 2	LEO	2 Jul 2007	8s 44p	Launched	71	ELISA	LEO	28 Feb 2010	8 10	Delivered	106	SEOSAR / PAZ	LEO		12 24	In build	
34	FOTON-M3	LEO	14 Sep 2007	9s 3p	Launched	72	Pleiades	LEO	28 Feb 2010	8 50	Delivered	107	NASA 8s10p	LEO		8 10	In build	
35	SAR-Lupe 3	LEO	1 Nov 2007	8s 44p	Launched	73	NigeriaSat-2	LEO	30 Apr 2010	8 10	Delivered	108	Genesis	LEO	31 Dec 2011	8 44	In build	
36	COSMO-2	LEO	9 Dec 2007		Launched	74	Cassiope	LEO	30 Apr 2010	8 16	Delivered	109	NuSTAR	LEO	31 Aug 2011	8 16	In build	
37	TecSAR	LEO	21 Jan 2008	10s 30p	Launched	75	LISA-Pathfinder	L1	30 Apr 2010	7 22	Delivered	110	SGEO	GEO	30 Jun 2011	10 32	In build	
38	SAR-Lupe 4	LEO	27 Mar 2008	8s 44p	Launched	76	GSAT-4	GEO	30 Apr 2010	10 24	Delivered	111	Sentinel-2	LEO	31 Oct 2012	8 72	In build	
39	SAR-Lupe 5	LEO	22 Jul 2008	8s 44p	Launched	77	RapidEye 6	LEO	30 Apr 2010	8 16	Delivered	113	AstroTerra	LEO	12 Sep 2012	8 52	In build	
44	RapidEye	LEO	29 Aug 2008	8s 10p	Launched	78	RASAT	LEO	30 Apr 2010	8 6	Delivered	114	GPM	LEO	21 Jul 2013	8 84	In build	
45	THEOS	LEO	1 Oct 2008	8s 50p	Launched		KSLV-1	LV	30 Apr 2010	8 1	Delivered	115	BepiColombo MTM	I/P	28 Feb 2014	24 24		
46	Chandrayaan-1	LLO	22 Oct 2008	10s 24p	Launched	79	KSLV-1	LV	30 Apr 2010	8 3	Delivered	116	BepiColombo MPO	I/P	28 Feb 2014	6 62		
							KSLV-1	LV	30 Apr 2010	8 10	Delivered							
							KSLV-1	LV	30 Apr 2010	84 2	Delivered							

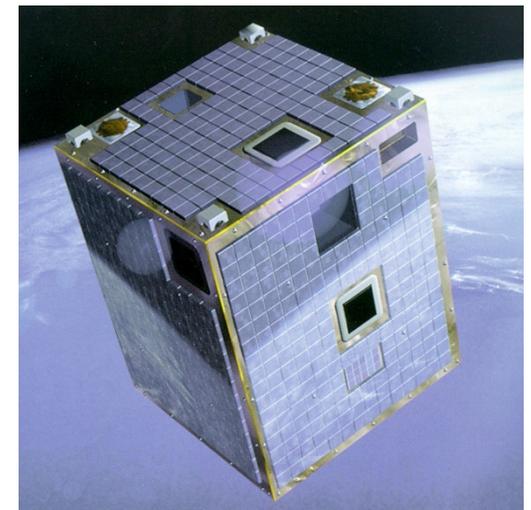
# Initial Li-ion Infusion (2000-2004)



- 2000 World's 1<sup>st</sup> Li-ion spacecraft battery launched
- The first ABSL lithium-ion battery contracts were 11<sup>th</sup> hour changes from other chemistries
- Interplanetary missions especially were tight for mass
- First contracts were for ESA science programs and a UK MOD mission
  - PROBA
  - Mars Express
  - Rosetta

## ESA Proba (Project for On Board Autonomy)

- Proba was designed to be a two-year technology demonstration mission, but has since had its lifetime extended as an Earth Observation mission
- Battery size
  - 21V, 9Ah (6s6p configuration with ABSL 18650HC Cell)
- Going on and on .....
- Launched October 2001
- > 40k cycles
- PROBA now in its eight year in orbit - the longest flying craft in-orbit powered by lithium-ion



## ESA Mars Express

- The first lithium-ion battery to reach Mars
- 6 month cruise phase, in orbit since Dec 2003
- Highly varied DOD 5-55%
- Battery size
  - 21V, 72Ah (3x6s16p configuration with ABSL 18650HC Cell)
- Going on and on ...
  - Launched June 2003
  - Mars Express has been granted three mission extensions. The latest until December 31, 2009



## Rosetta - ESA Cornerstone Mission

- Rosetta will rendezvous with comet in 2014
- Carries a lander, RoLAND, the first ever to land on a comet (67P)
- Battery size
  - 21V, 49.5Ah
  - 3x6s11p configuration
  - ABSL 18650HC Cell
- Both orbiter and lander powered by ABSL lithium-ion batteries
- Status
  - Both batteries performing nominally, multiple cycles during planetary flybys



## Lithium-ion Maturity

- ABSL Li-ion now well proven, but new challenges arose
  - Range safety
    - Development of lithium-ion procedures
  - Competition (other vendors now had flight heritage)
    - SAFT
    - Yardney
    - GS
  - Need for high power and high voltage systems
  - Manned safety
  - ITAR (even more)

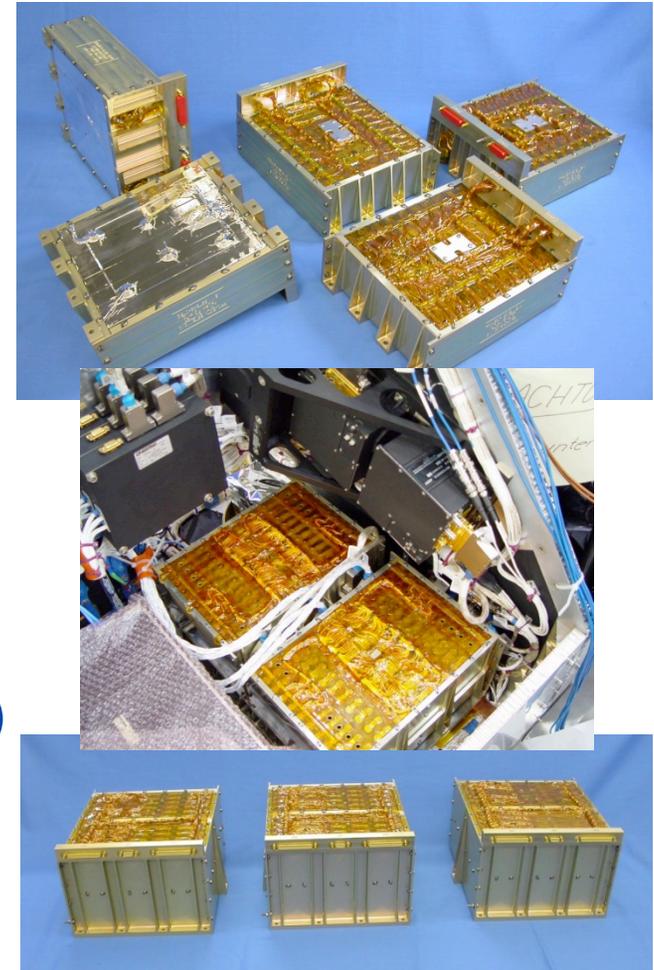
## Lithium-ion Maturity

- Main ABSL developments
  - COTS approach complemented HC cell with two additional space proven cells
  - Issued generic range safety advice
  - Expanding the use of battery modularity
  - Met increasing battery capacity demands
  - Built up a domestic operation inside the ITAR boundary
    - Registered US small business
    - Full design, manufacturing & testing facility located in Colorado (50 miles NW of Denver)

# Expanding use of modularity



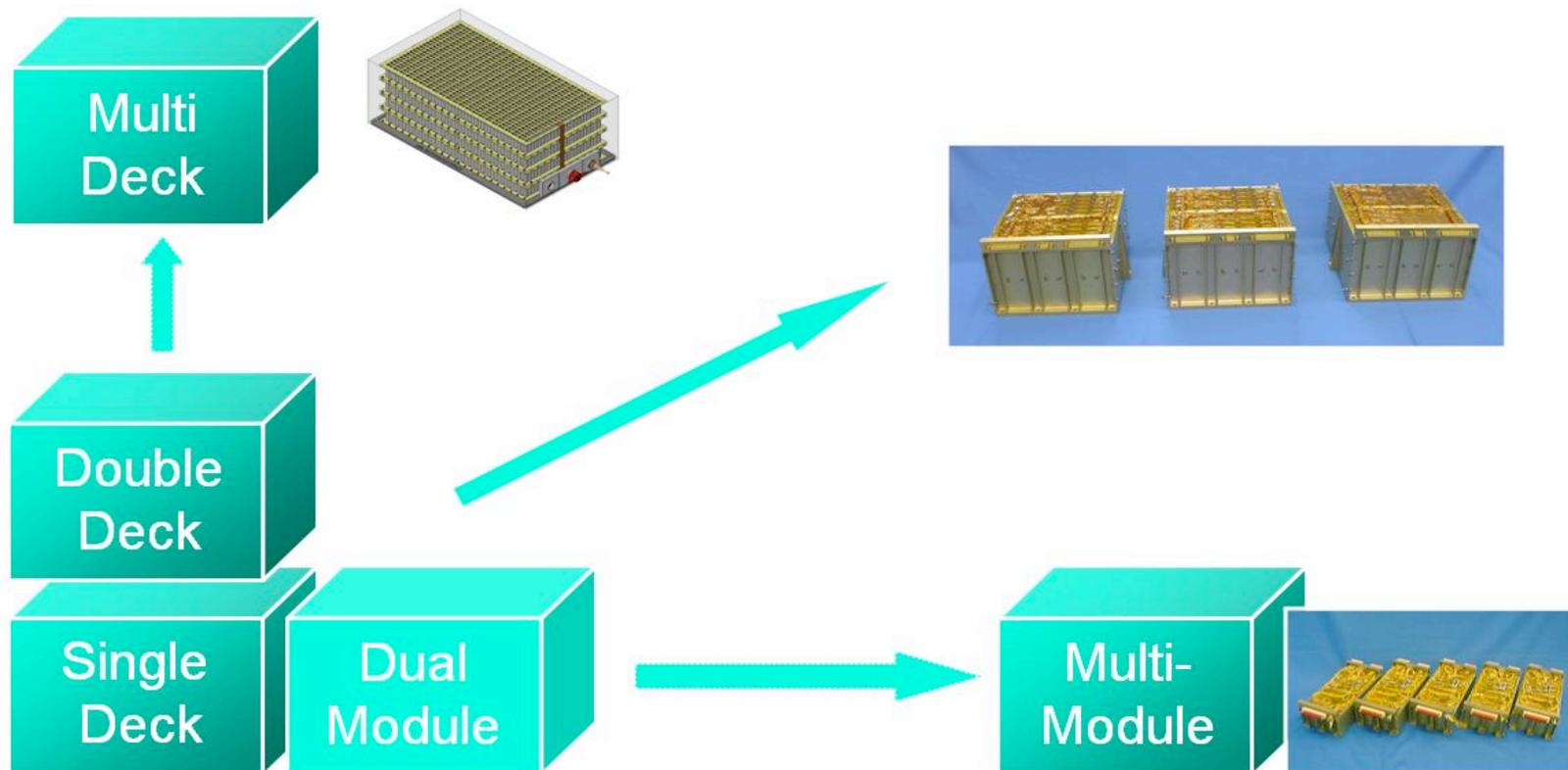
- BTP solutions were not confined to single battery systems:
  - GIOVE-A (MEO, first Galileo s/c)
    - 4 - 9s10p Modules
  - SAR-Lupe (10 yr LEO)
    - 5 spacecraft constellation
    - 2 - 8s44p Modules
  - TerraSAR-X (7.5yr Commercial LEO)
    - 3 - 12s24p Modules



# Use of modularity

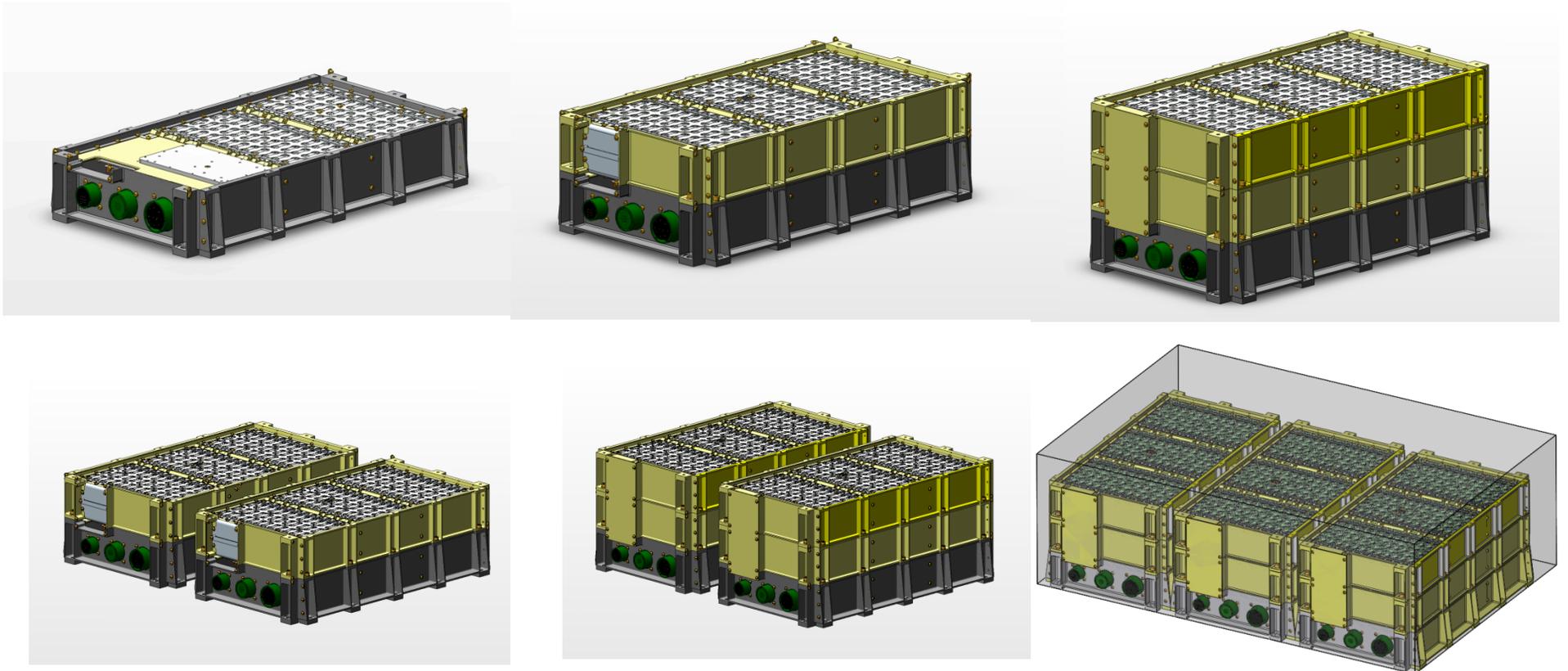


- Modularity provides flexibility
- Allows architecture to expand vertically, horizontally, and/or into multiple modules



# Use of modularity

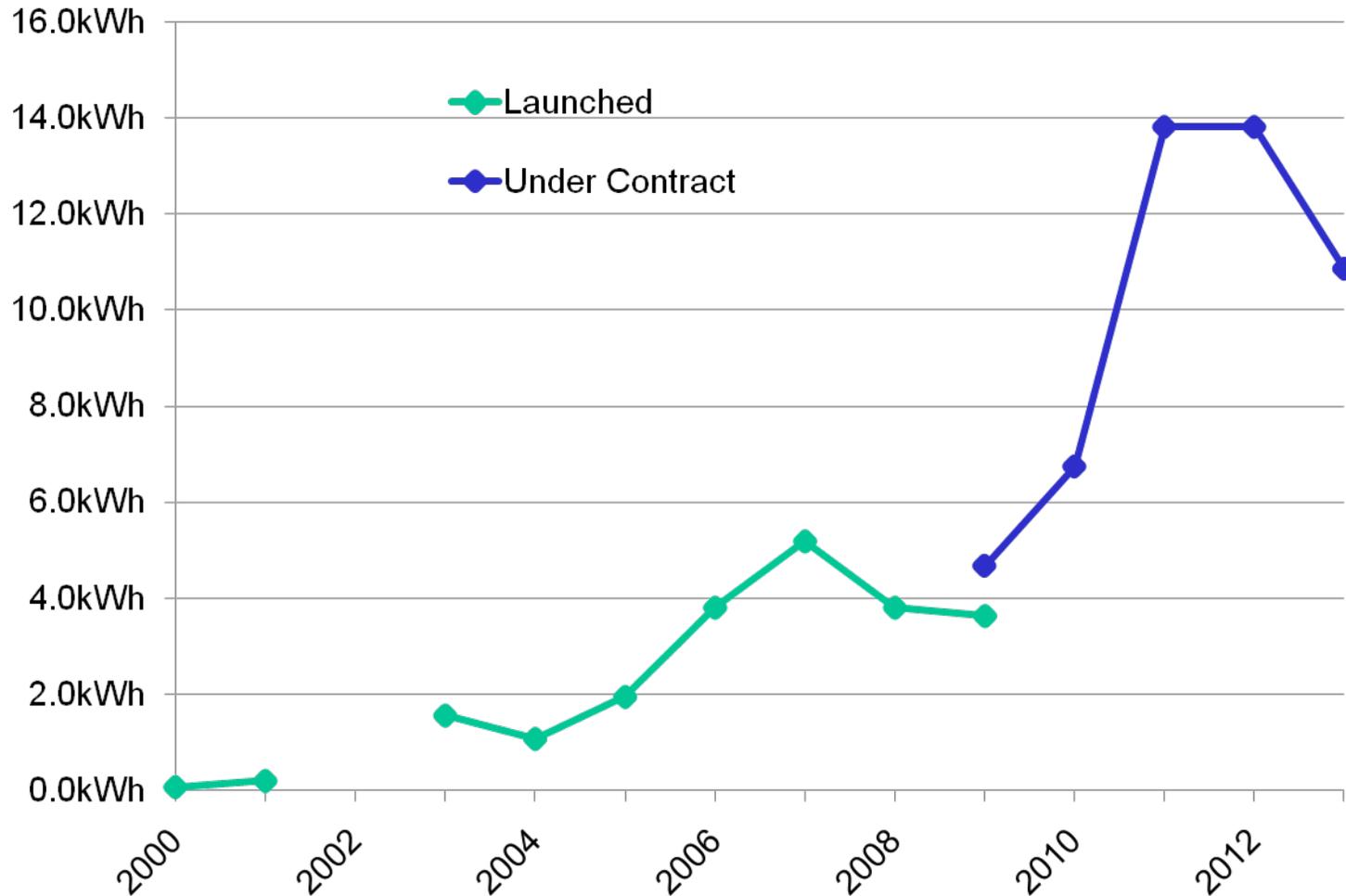
- Modularity design flexibility



# Battery Size Evolution

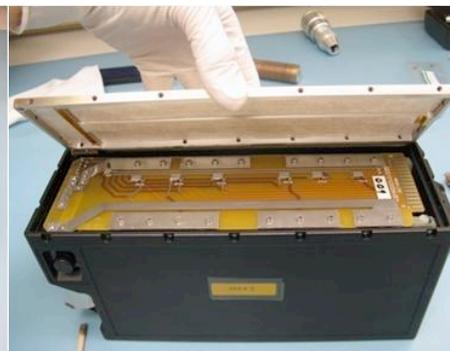
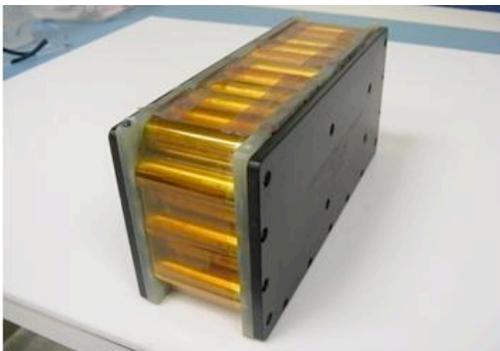
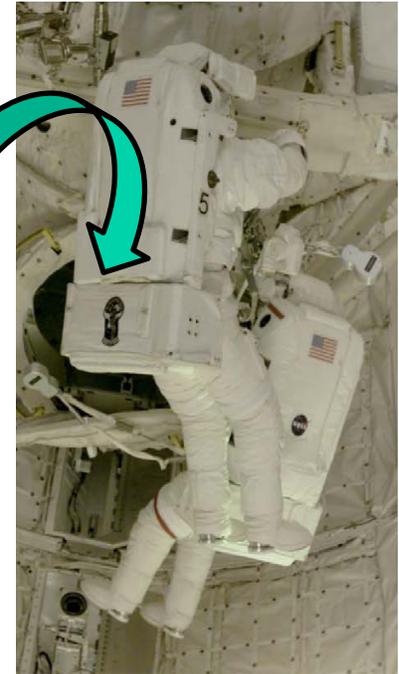
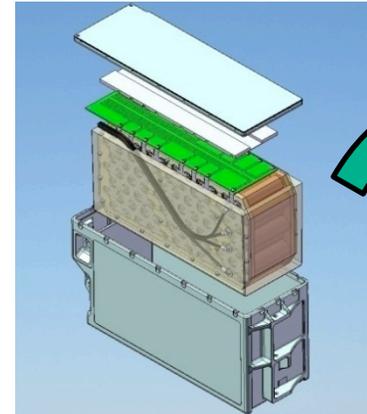


## Chart of biggest ABSL battery launched in each year



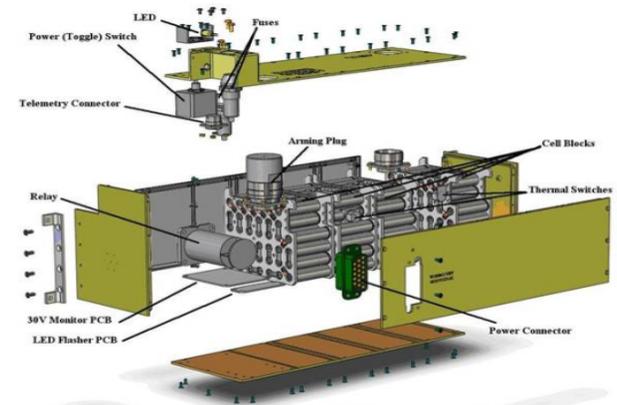
## Extravehicular Mobility Unit (EMU)

- NASA JSC
- 190 Wh/kg energy density (cell)
- Integrated into existing interface



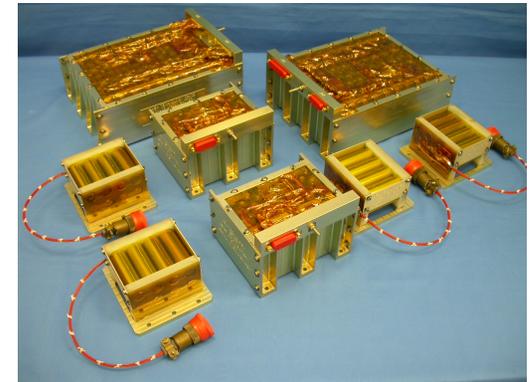
## Muscular Atrophy Research and Exercise System (MARES)

- ESA/NASA (via NTE)
- First 270V Lithium-ion battery aboard the International Space Station
- Drop in replacement for the previous Nickel-Cadmium battery



## KSLV-1

- Although the satellite payload was lost due to a separation failure, the performance of the batteries was completely nominal
- ABSL qualified and delivered a full suite of lithium-ion batteries
  - High energy
    - Flight Termination Systems
    - Pyrotechnic systems
    - Avionics systems
  - High power and high voltage
    - Thrust Vector Control - an industry breakthrough as it was the first launch of a high voltage lithium-ion system
- Flown in 2009



## Reaction Mass Actuator

- Battery comprises 2 series connected modules
- Each module 100s1p (200s1p system)
- 4 battery systems delivered (prime & spare)
- ABSL delivered 600V hardware in less than three months





## Reaction Mass Actuator

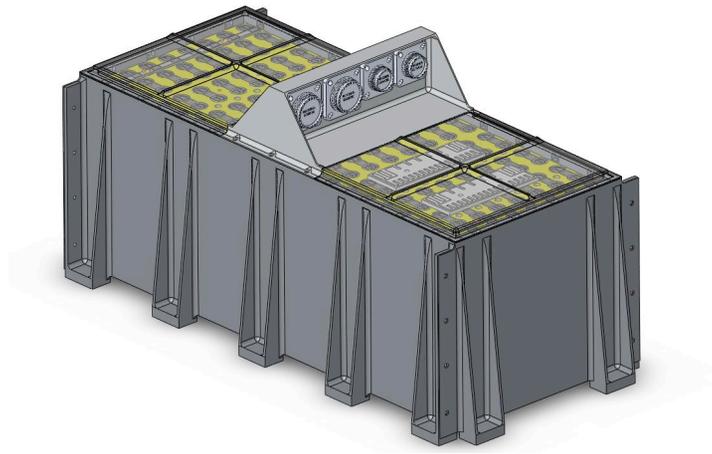
- Both ABSL NP and BC cell used
- Next generation high power system

### Comparison of Current Cell Capability with Previous Generation Cell

	C Rate	Attributes	Application
Previous Gen ABSL 18650 HR Cell	> 10 C	High current delivery	KSLV, MARES
Next Gen ABSL 18650 NP Cell	> 30 C	Very high current, long life, safety	IPP, RMA
Next Gen ABSL 18650 BC Cell	> 30 C	High Power	Scorpeus, RMA

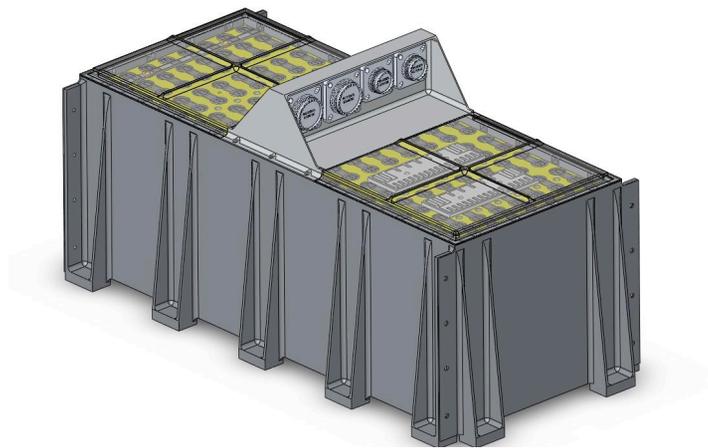
## SGEO

- First ABSL commercial communication GEO contract
- 5 - 7 kW Bus
- 15 year GEO mission
- Space insurers value the highly fault tolerant ABSL cell array compared to large cells
- First spacecraft launch 2011/2012



## SGEO (cont)

- Multiple module battery allows battery to be scaled to suit payload demands
- Battery to power spacecraft during eclipse and electric propulsion use throughout the 15 year lifetime
- Module size - 10s32p (8 modules on first platform)
- Battery total mass 130 - 140kg
- Battery Energy - 13.8kWh

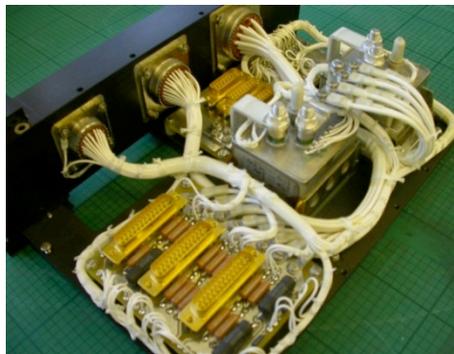
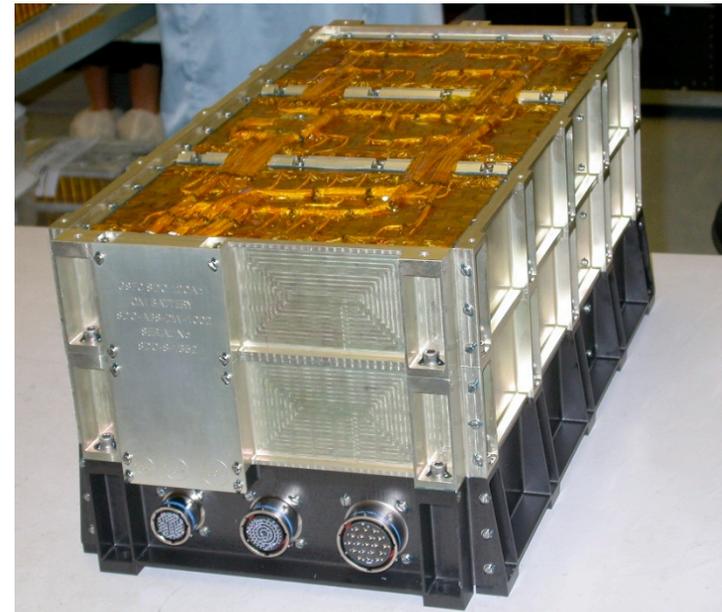


# GEO Missions



## SDO

- NASA flagship mission
- 12 year GEO mission
- 4.5 kW Bus



# GEO Missions



## GSAT-4

- Indian communications satellite mission
- 10 year GEO mission



## USG Mission

- US Government GEO mission



# ABSL Li-ion at the end of 2009



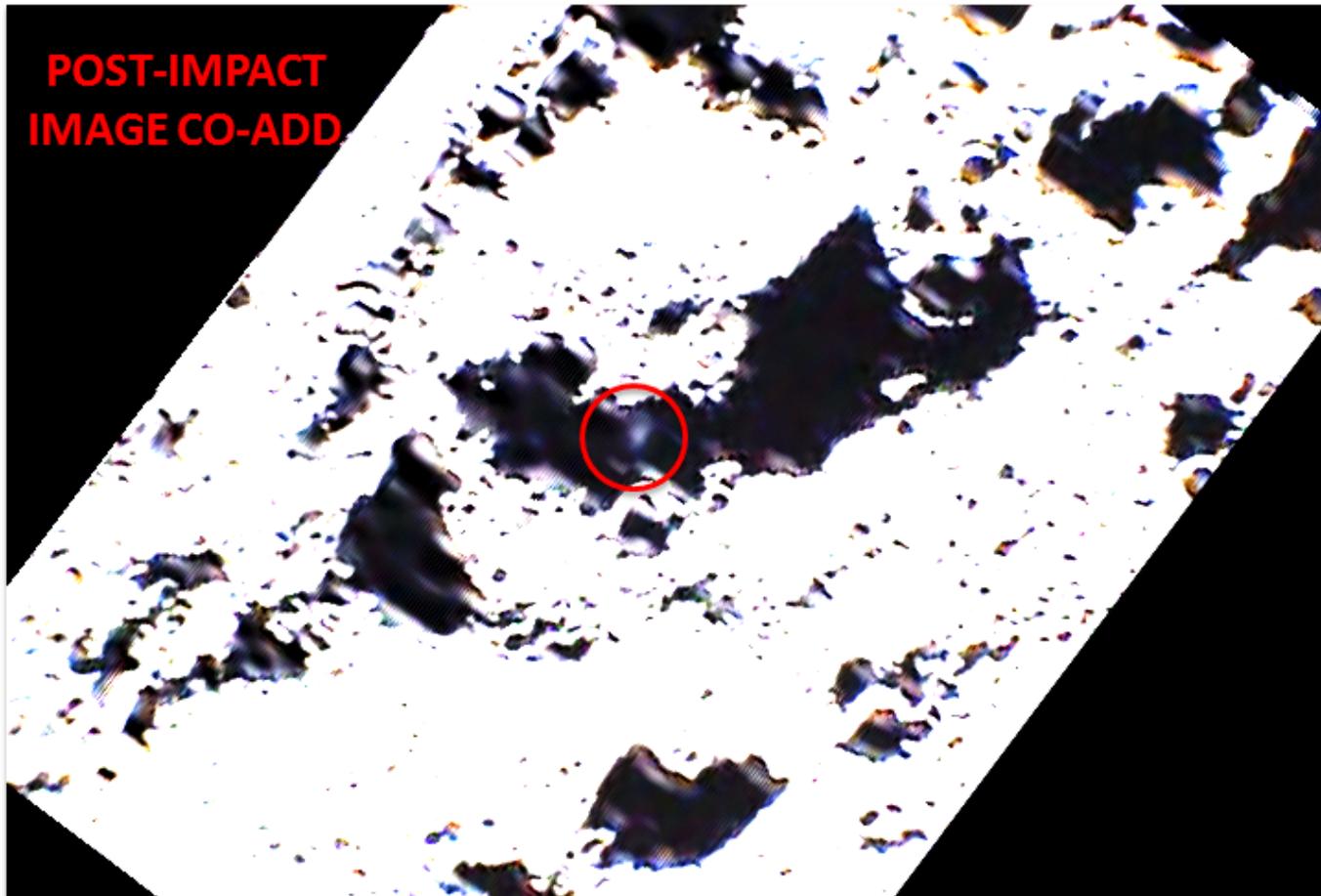
- 61 spacecraft powered by ABSL lithium-ion launched
- Additional 53 launches under contract including 4 GEO
- Largest system flown: 132Ah
- 34 existing module designs ranging from 3Ah to 156Ah and 7V to 300V
- Contracts for 16 NASA spacecraft batteries + 35 EMU flight batteries
- Four COTS cell types flown
- World's first 270V lithium-ion battery in space
- Flight batteries for manned and unmanned space programs built in CO
- Powering 1<sup>st</sup> spacecraft in the European Galileo (GPS) constellation
- Customers still have reliability as a top priority for selection, but cost is much more important now as the technology has become established

# ABSL Going Forward



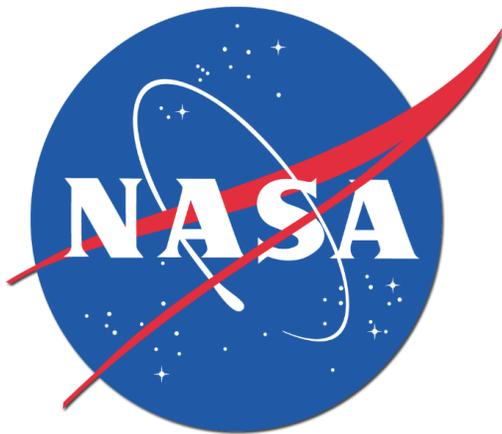
- ABSL recently won a contract for a 378Ah system for a USG program
- ABSL expects first launch of the new 190Wh/kg high energy cell this year
- ABSL has two excellent high power cells for launch vehicle and high current payloads
- ABSL continues to assess new cells and is currently assessing technologies well in excess of 200Wh/kg
- ABSL will continue to branch into commercial GEO market
- ABSL will build on Colorado success to pursue more USG/Commercial work

## VisibleCamera Images from LCROSS Shepherding Spacecraft





Acknowledging those involved in the ABS L Li-ion program  
from the inception at the beginning of the decade



**Thank You**