SORCE

Flexible Satellite Architecture Allows Science to Continue Despite Hardware Challenges

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Presentation Agenda

- The Beginning
- The Middle
- The Beginning of the end
- DO-OPs
- The Afterlife
- The End

Circumstances leading to a new ops concept

THE BEGINNING

Jan 25 2003 – Launch Day

- SQL Slammer
  - A large internet worm infected world wide and caused a major slowdown of the internet as routers started to fail
- Pegasus Launch vehicle alignment took longer than expected, then the GPS did not come up properly
  - Turn it off and turn it back on again
- 3-2-1 Drop
- Can you hear me now
  - One of our primary antennas was configured with an uplink of 1000W instead of 16W
- Reaction Wheel turned off

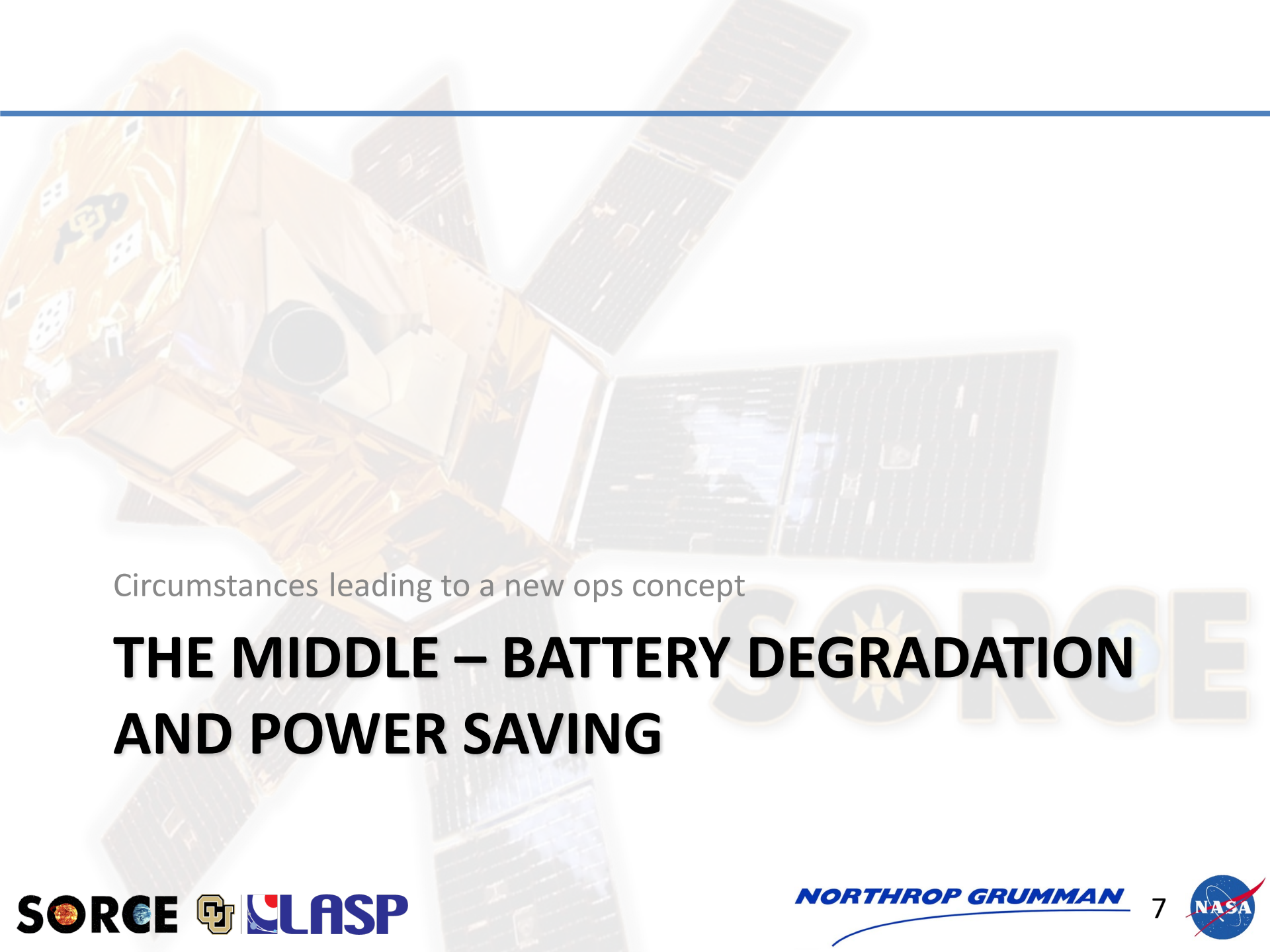
Credit KSC

Jan 26 2003 – Launch Day (2)

- Be careful what you ask for
  - The day two shift report made reference to slow and steady progress and a tortoise
  - S/C developed problems flipping back to front
    - The Operations team began to refer to this as turtle mode

Launch Continued

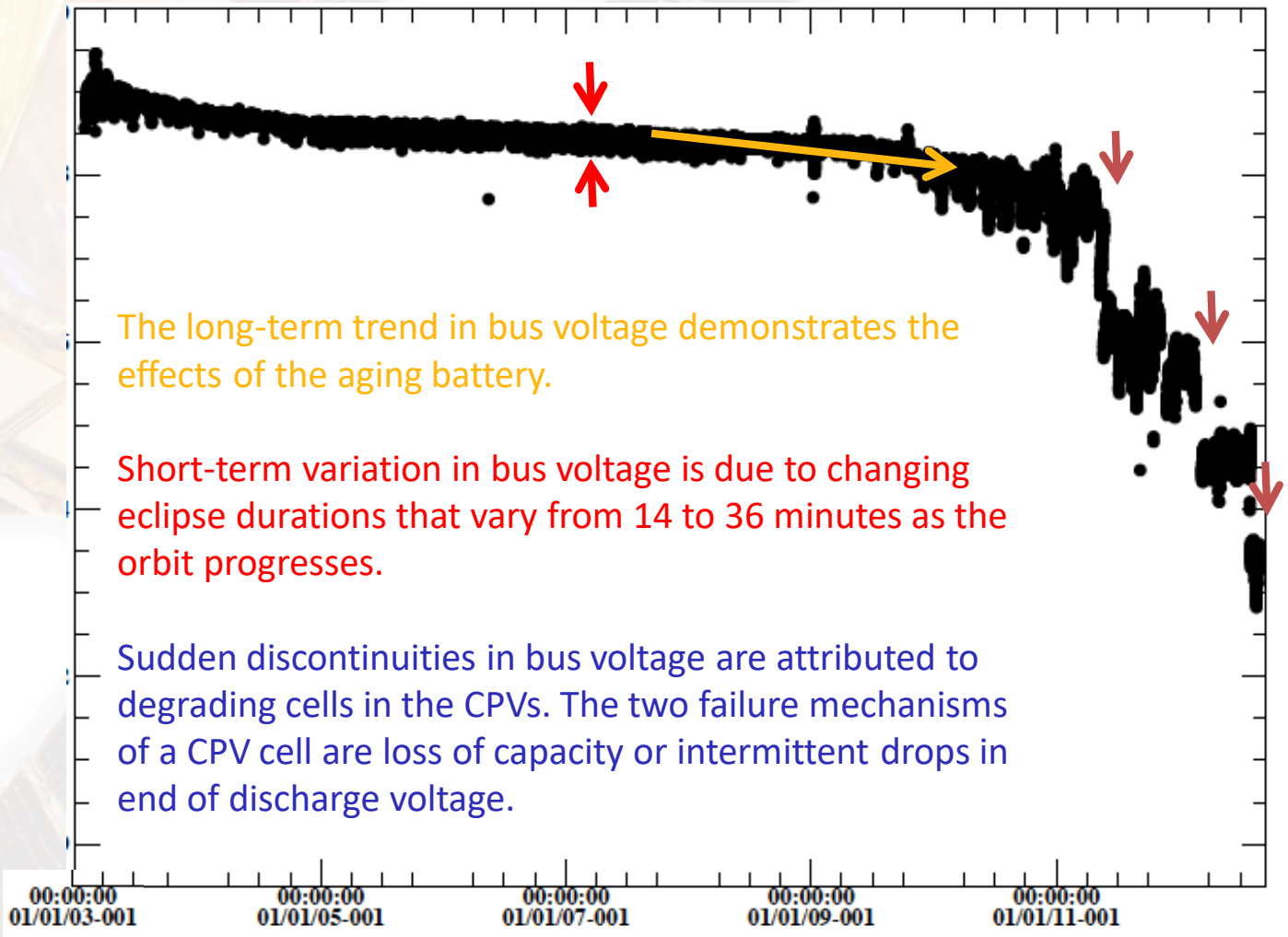
- Day 5 - Primary S/C checkout complete, S/C transitioned to normal solar pointing
  - Twice
- Day 7 – Turn on TIM
  - Made it 4 orbits before the first GCI lock-up
- Day 37 – Let there be light
  - All instruments collecting science data



Circumstances leading to a new ops concept

THE MIDDLE – BATTERY DEGRADATION AND POWER SAVING

Historical Battery Performance

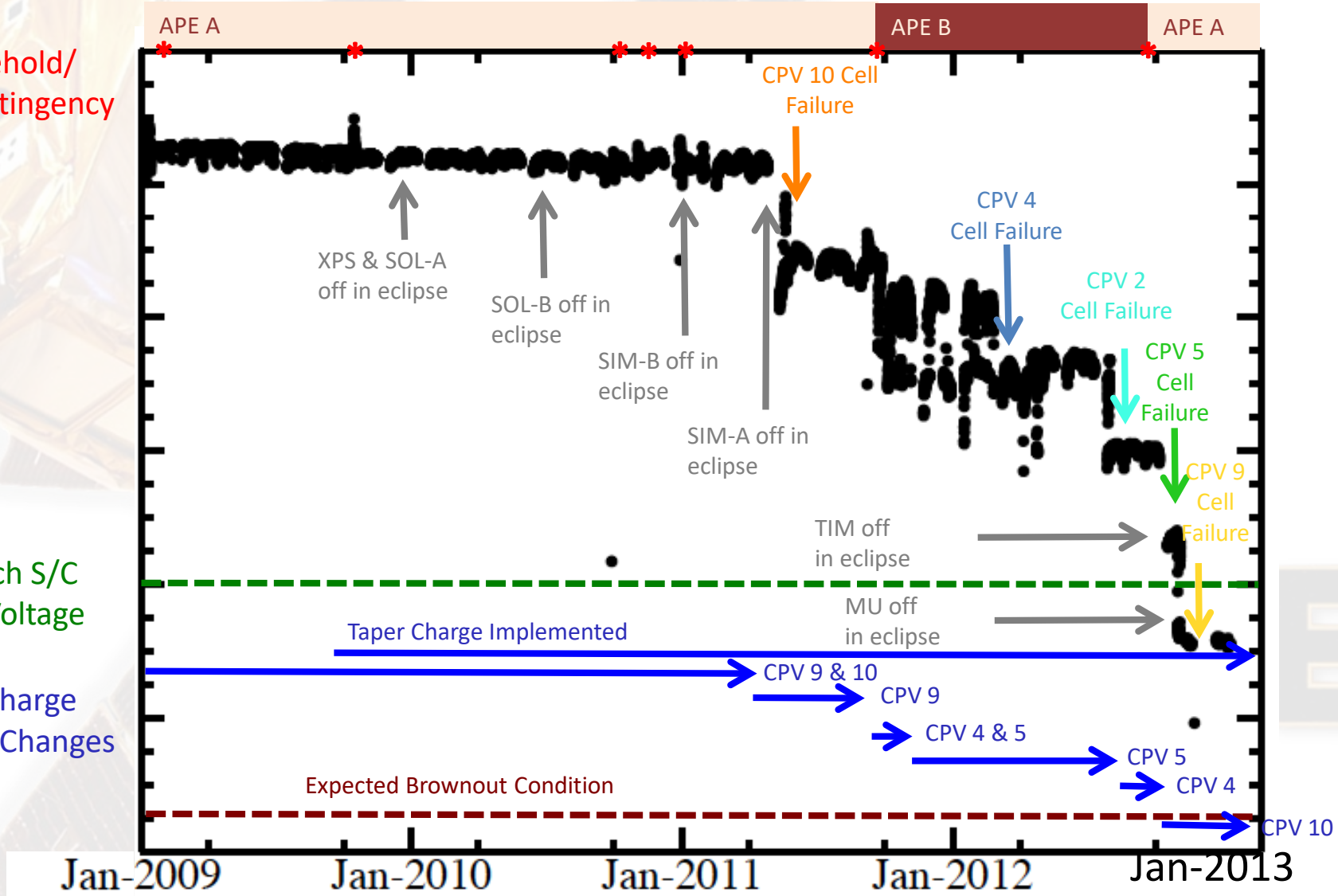


The long-term trend in bus voltage demonstrates the effects of the aging battery.

Short-term variation in bus voltage is due to changing eclipse durations that vary from 14 to 36 minutes as the orbit progresses.

Sudden discontinuities in bus voltage are attributed to degrading cells in the CPVs. The two failure mechanisms of a CPV cell are loss of capacity or intermittent drops in end of discharge voltage.

Historical Battery Performance

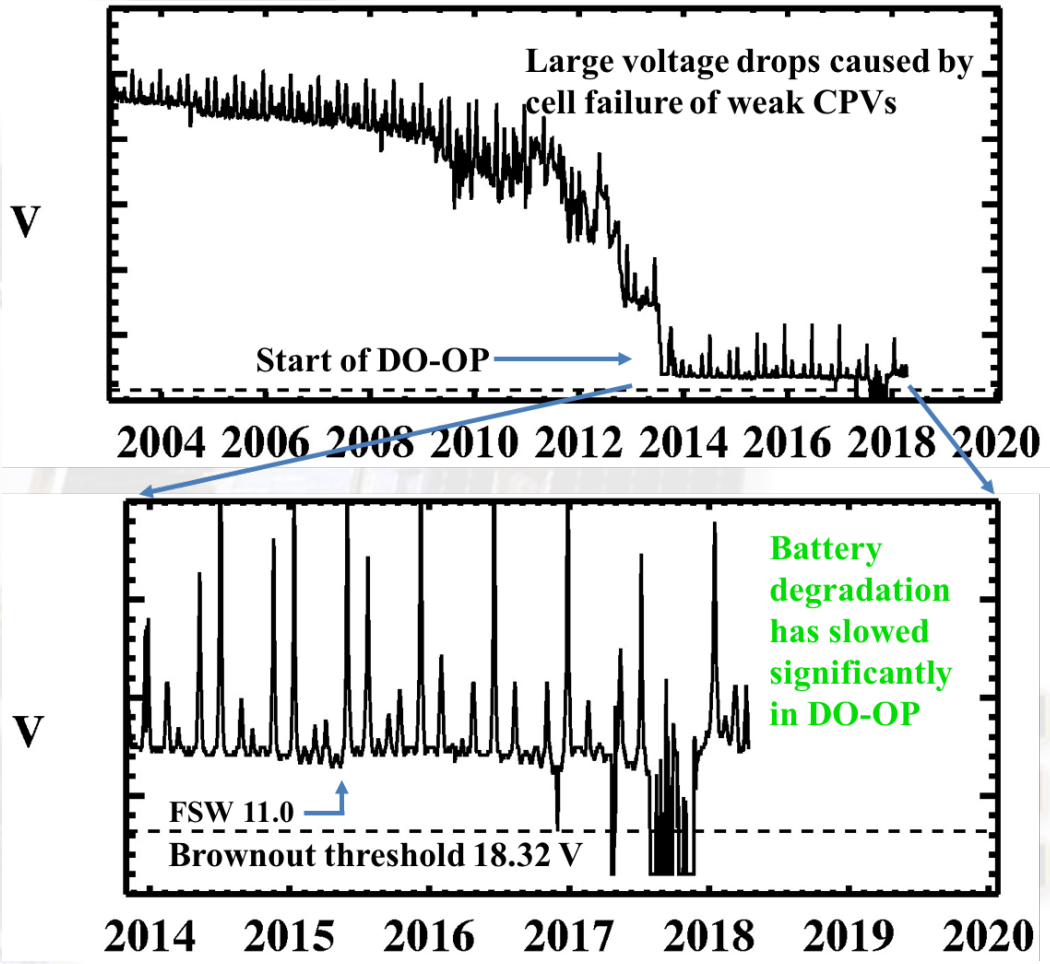


Circumstances leading to a new ops concept

THE BEGINNING OF THE END

Emergency Mode

- July 30, 2013 SORCE entered Emergency Mode as the battery could no longer sustain the load of the primary computer through eclipse. (CPV 5 and 9)
- Emergency mode endured for 78 days of 24x7 coverage before the spacecraft was stabilized, but it was still unable to collect science.
- Major challenges were overcome during this time period, including:
  - Installing momentum bias to ensure stable sun pointing at sunrise
  - Loading a new APE FSW to control loads on/off based on solar array current



Christmas Eve 2013 – Completed the SORCE to TCTE science overlap

Circumstances leading to a new ops concept

DO-OP – Daylight Only Operations

Orbit in the Life: Eclipse

- All non-critical loads off in eclipse:
  - Primary Computer (OBC)
  - Instruments, MU
  - RWAs, MTBs, Star Tracker
  - Heaters
  - Transmitter

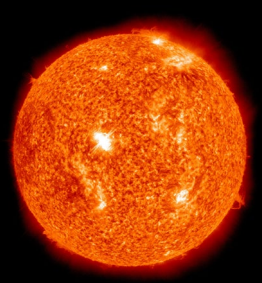
- Spinning about Z-axis to maintain pointing
  - 0.5 deg/second
- No Science Collection
- No Data Stored beyond the low voltage watermark
- No communication with the spacecraft

Orbit in the Life: Sunrise

- Solar Arrays and Coarse Sun Sensors detect the Sun and begin to turn loads
- Spacecraft stops spinning and transfers momentum to RWAs

- Communication with ground reestablished ~2 min after sunrise
- Primary computer boots and checks configuration of the S/C, restoring flight software to the backup computer if necessary via “Boot to Bank 2”
- Once S/C is fully configured and stable exits Safehold and is ready to be configured for Science Mode

Orbit in the Life: Day

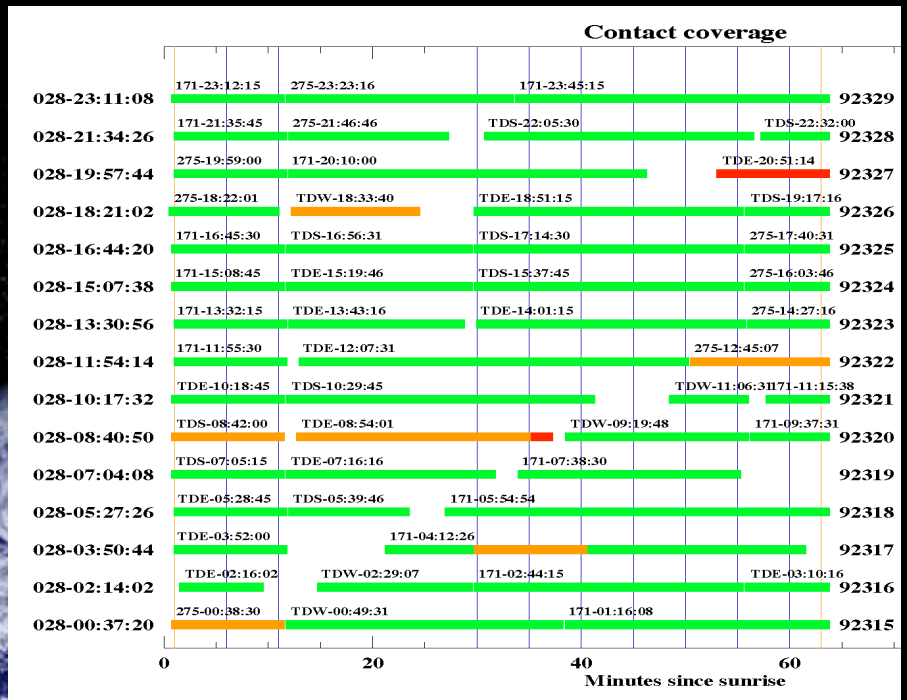


- Once science attitu
  achieved, S/C detec
  enables science sequences

- Ground autonomy loads ATS with commands to science attitude

- ATS commands prime science and special calibrations

- Science data are captured by TDRS satellites and recorded by the ground



Orbit in the Life: Sunset

- ATS commands spacecraft to safe state 5 minutes prior to sunset
  - Loads off
  - Enter Safehold (APE control)

- Ground Automation confirms safe configuration, prepared to send commands to make spacecraft safe if necessary
- As solar array current begins to fall, momentum transfers from RWAs to the S/C body initiating a slow roll to maintain pointing throughout eclipse
- Communication blackout at sunset

THE AFTERLIFE

Communications Outages

- Fall of 2018 the battery voltages started routinely falling to new lows
  - Every component on the S/C turns off
- Occasionally the operations team would not be able contact the SORCE for a few orbits
  - Battery temperatures > 90C
  - Battery performance improved until April 2019
- Low battery voltages led to an extended outage which lasted for 89 orbits (but who is counting)
  - 6 days
  - Tweaked operations concept and regained reliable communications.
- July 2019 (KDP-F) approved extending operations through January

THE END

Final Days

- 1/27/20 — Passivation Tabletop with NGIS
- 2/2/20 — WHPI campaign complete
- 2/10/20 – 2/21/20 — Engineering tests with NASA
- 2/19/20 — Aux B command test
- 2/20/20 — Passivation Rehearsal (flatsat)
- 2/25/20 — Passivation Day – Collect data up to the final orbit
- 2/25/20 – 3/11/20 — Monitor for RF
  - SN – 10 minutes every sunrise 3 days/ week
  - SN – One full orbit 3 times/ week
  - GN – Two orbits/ week, timed early, mid and late orbit day

Conclusion

- The experiences of the SORCE flight operations team offers an excellent example of innovative engineering using limited resources.
- The end result is a mission extended well beyond its designed life continuing to return important data to the science community to extend the climate record.

Daylight-Only Operations (DO-OP) made possible with new Flight Software to both the primary and backup computers.

Added years of life to the SORCE mission and enabling the cross-calibration with TCTE and TSIS.

Special Thanks

- Orbital/OSC/NGIS – Dave, Grace and Alan
- GSFC – Eric
- White Sands – Operators and Scheduling group
- LASP
  - Deb
  - Tom
  - Operations team – professionals and students
  - Science and mission support teams

The continuation of this mission is made possible by the hard-working members of the SORCE team, which extends beyond the operations cadre to include the Northrop Grumman engineering team, the dedicated SORCE scientists, the White Sands Ground Scheduling Group, and the technical management team at NASA Goddard. All should be proud of their contribution to help SORCE continue its important mission.

Questions?

Contact LASP

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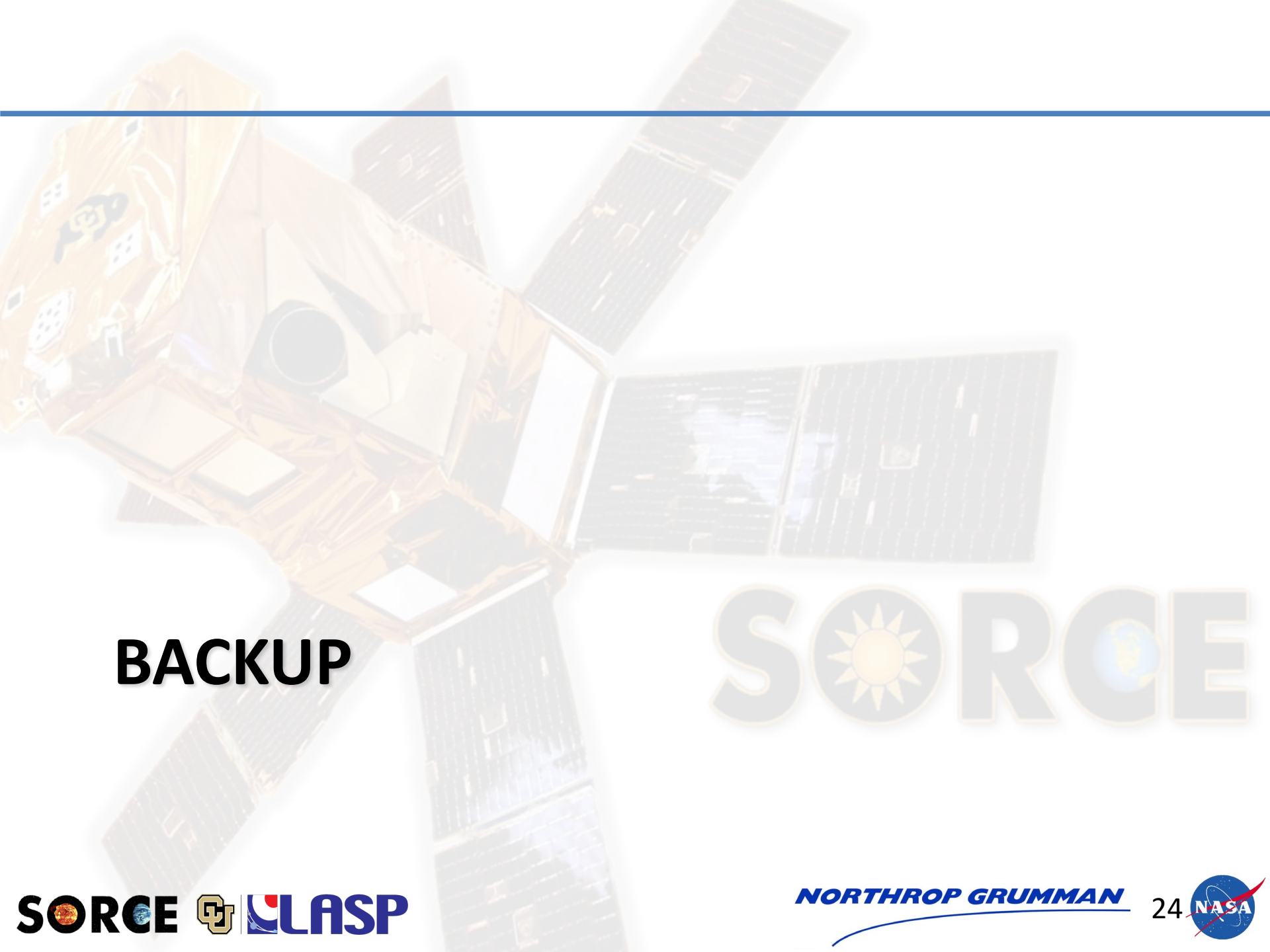


BACKUP

Acronym List

- APE = Attitude Power and Electronics
- ATS = Absolutely Timed Command Sequence
- B2B2 = Boot to Bank 2
- CEU = Central Electronics Unit
- CPV = Common Pressure Vessel
- CSS = Coarse Sun Sensor
- DO-OP = Daylight-Only Operations
- FOT = Flight Ops Team
- FSW = Flight Software
- GCI - Generic Channel Interface
- GN = Ground Communications Network
- LASP = Laboratory for Atmospheric and Space Physics
- MU = Instrument Microprocessor Unit
- OBC = Onboard Computer
- RTS = Relatively Timed Command Sequence
- RWA = Reaction Wheel Assembly
- SIM = Spectral Irradiance Monitor
- SN = Satellite Communications Network
- SOLSTICE = Solar Stellar Irradiance Comparison Experiment
- SORCE = Solar Radiation and Climate Experiment
- SSI = Solar Spectral Irradiance
- ST = Star Tracker
- TDRSS = Tracking and Data Relay Satellite System
- TIM = Total Irradiance Monitor
- TMON = Telemetry Monitor
- TSI = Total Solar Irradiance
- XPS = XUV Photometer System

Operations & System Overview

SORCE OVERVIEW

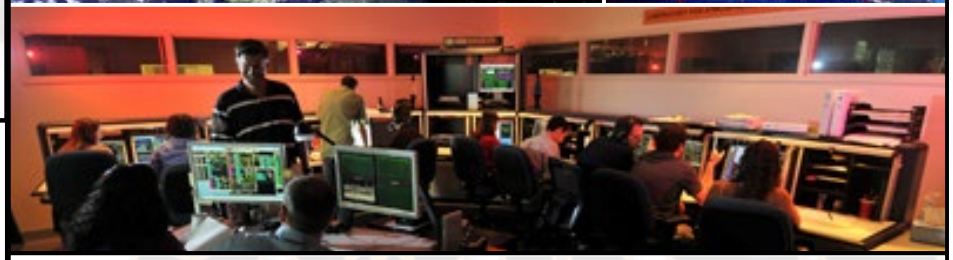
Mission Overview

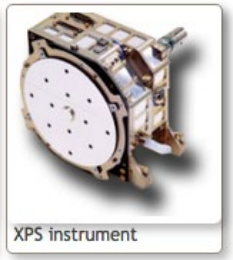
Mission Details

Launch - January 25, 2003 (Pegasus XL)
Orbit
Planned - 645 km, 40° inclination, 96 minutes
Current - 584 x 619 km, 40° inclination, 96 minutes
Science Payload:
TIM – *Total Irradiance Monitor*
SIM – *Spectral Irradiance Monitor*
SOLSTICE – *SOLar STellar Irradiance Comparison Experiment*
XPS – *XUV Photometer System*
Flight Operations - LASP
Science Data Processing – LASP
Duration – Nominal 6 year mission exceeded in January 2009; extended ongoing (16th year)

SORCE Science

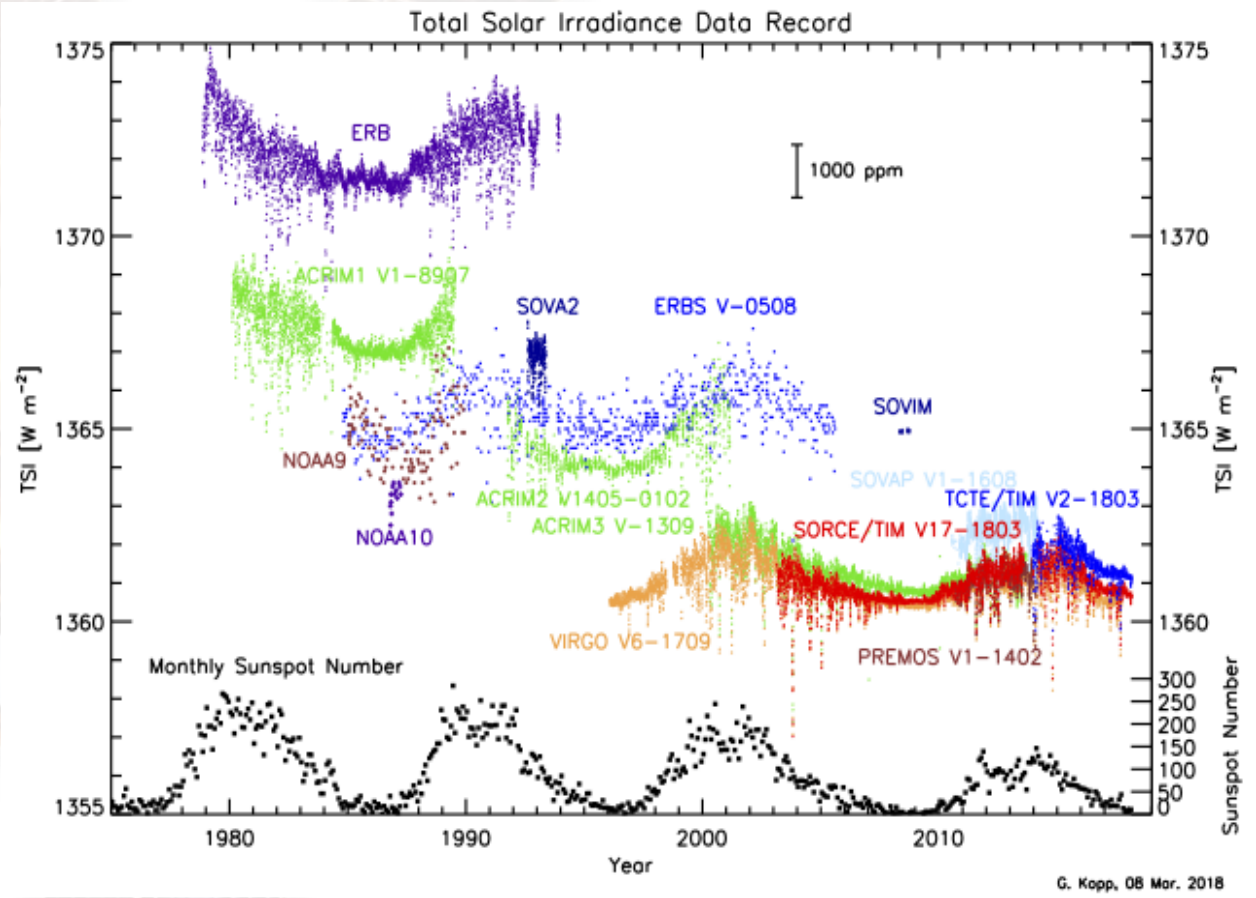
SORCE measures the Sun's output with the use of state-of-the-art radiometers, spectrometers, photodiodes, detectors, and bolometers engineered into instruments mounted on a satellite observatory. Spectral measurements identify the irradiance of the Sun by characterizing the Sun's energy and emissions in the form of color that can then be translated into quantities and elements of matter. Data obtained by the SORCE experiment will be used to model the Sun's output and to explain and predict the effect of the Sun's radiation on the Earth's atmosphere and climate.





Science Overview

- Solar radiation is the dominant energy source in the solar system and understanding of its variation is critical for atmospheric and climate studies.
- The TSI and SSI records are essential components of the national climate program with the continuous TSI data record going back to the Earth Radiation Budget instrument in 1979.



- Providing simultaneous measurements of TSI improves the long term accuracy of the dataset

Spacecraft

ACS

- RWAs (3 of 4 operational)
- Star Trackers (1 of 2 operational)
- FSS, MTBs, TAMs
- CSS (8 total)

EPS

- 6 Panel Solar Arrays
- 23 Amp-hr Nickle Hydrogen Battery (11 common pressure vessels, 22 cells)

Onboard Computers

- CEU (sides A&B)
- APE (sides A&B, Banks 0*-2)
- MU (Instrument Module)

Flight Software

- CEU – can be modified/ burned to EEPROM
  - On-board RTS's – can be modified
- APE – Bank 2 can be modified/ burned to EEPROM
  - * Bank 0, launch/ boot version can not be modified
- MU – can be modified/ burned to EEPROM

DO-OP Design Challenges

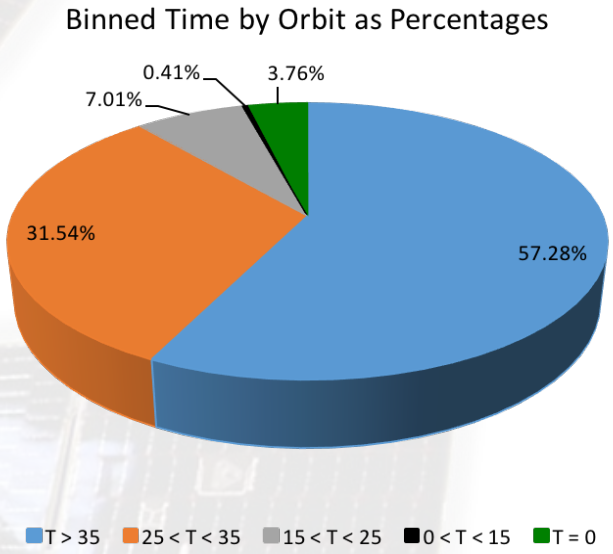
Powering off the primary computer to survive each eclipse had severe consequences to volatile memory storage on the spacecraft. Locations in memory used to store the ATS and captured science data were erased each sunset. Several challenges had to be overcome in order to continue the TSI and SSI records, these included:

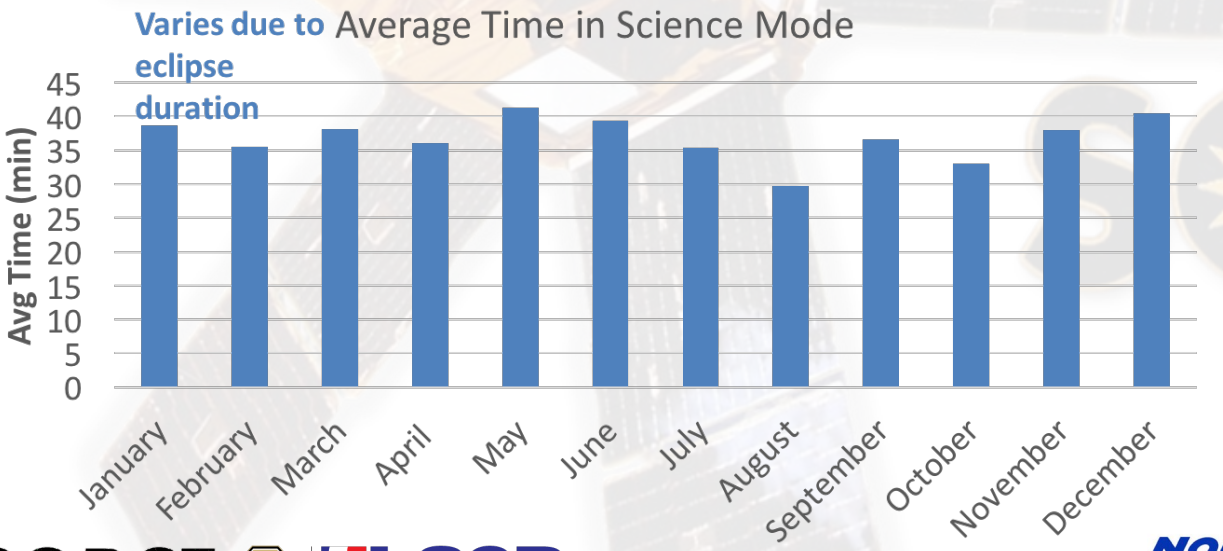
1. Allowing the spacecraft to autonomously promote to science attitude safely
2. Scheduling and collecting science autonomously and robustly given uncertainty in timing, modes
3. Sending science data to the ground before computer powered off in eclipse
4. Ensuring the spacecraft remains safe through redesigned fault protection

Achieve Science Attitude Autonomously

Statistics from 2018 DO-Op Mode

- High success rate for achieving Science Mode (98% of orbits)
- Average time in Science mode per orbit nearly 37 minutes





Performance is trended yearly and shows strong repeatability of science return in DO-OP mode.

Science Success

2018 Statistics

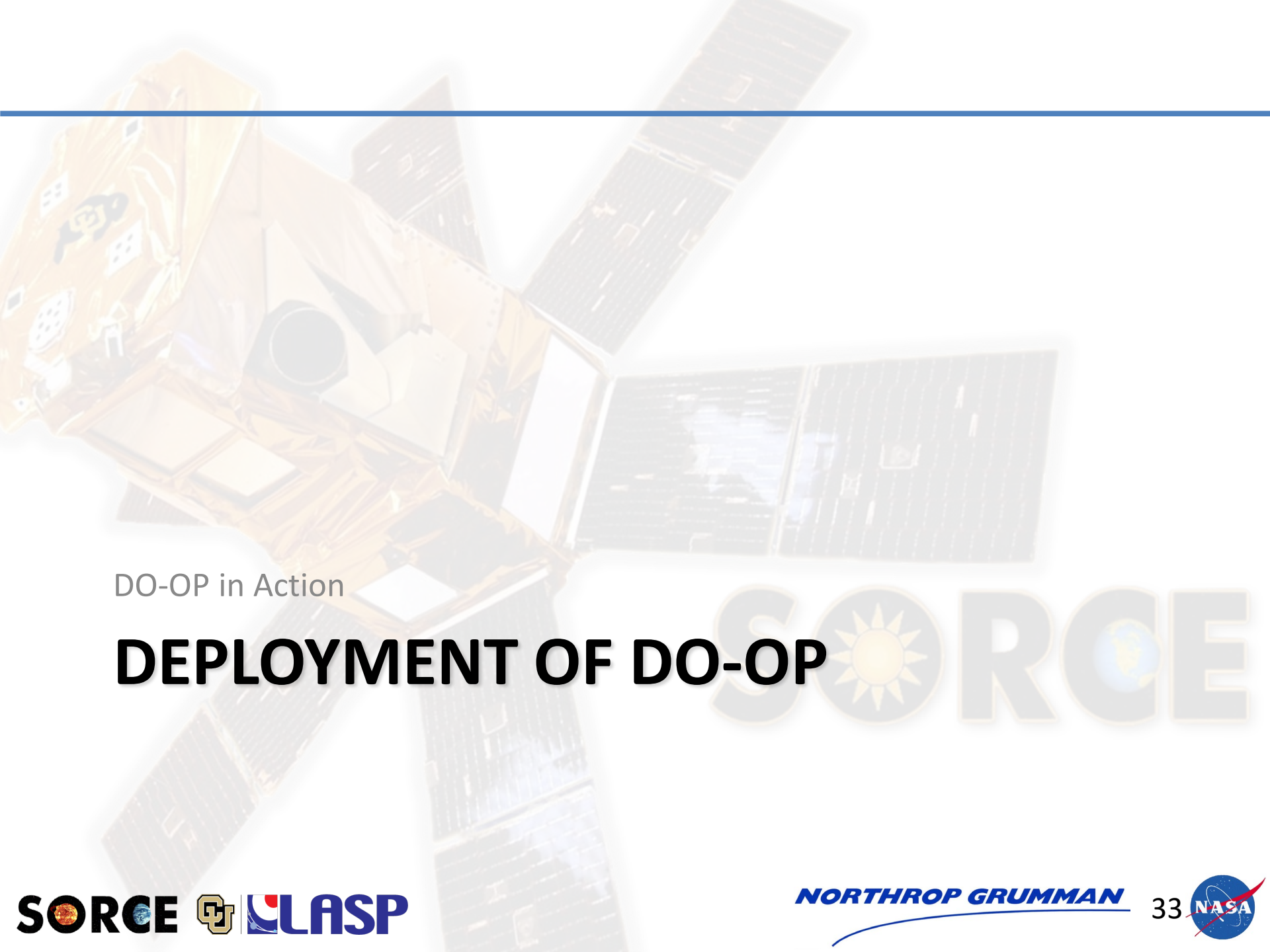
Instrument	Experiment/Calibration	Requirement	Total %
SIM A	Quick Scan 24	1 full scan per day	92
	ESR Scan	1 complete scan per month	92
	Servo Calibration	4 per month (2 Gain, 2 Gain50)	100
SIM B	Quick Scan 24	1 full scan per month	92
	ESR Scan	1 complete scan per month	42 *
	Servo Calibration	2 per month (1 Gain, 1 Gain50)	100
SOL A/B	FUV Scan	1 full scan per day	100
	MUV Scan	1 full scan per day	100
	Filter Calibration Scan	2 scans per month	100
TIM	Normal Solar	1 orbit per day (7.1%)	100
	Degradation A,C & Aliveness D	50% of scheduled calibrations are successful	100
XPS	65s Integration	1 integration per day	100
	Calibration	1 every 30 days	100

Science performance vs. requirement is evaluated each year during SORCE's annual review.

Each year since transitioning to DO-OP mode in 2014, SORCE science requirements have been met or exceeded.

This robust operations concept has helped further the TSI and SSI climate records.

* Requirement not met for a period of time due to scarcity of experiment being scheduled and timing of brownout operations. Experiment was redesigned to be successful with shorter orbit days



DO-OP in Action

DEPLOYMENT OF DO-OP

Science Automation

- **At sunrise the S/C is spinning at ~0.5 deg/sec, with 0 RPM wheel speeds**
- **The APE detects sunrise by monitoring CSS currents**
  - Wheels are spun up as momentum is transferred from the spacecraft to the wheels
  - About 4.5 minutes for completion of spacecraft spin-up
- **The S/C maneuvers to solar pointing attitude**
  - About 2 minutes to complete
- **Once the APE detects the solar array current has been above 20A for 60 seconds, declares sunrise**
  - 20 A is achieved when the S/C points to within 45 degrees of the sun
  - Turns on OBC, MU, Heaters, FSS
- **OBC boots, checks for nominal safe mode entry and that the APE has not reset**
  - About 1 minute to complete
  - If the nominal/expected condition is met, the exit safehold sequence is enabled (RTS 17, see subsequent slides)
- **Once the OBC detects 60 seconds of stable solar pointing it initiates the exit safehold sequence and enters contingency mode**
  - The transition from safehold to contingency has historically taken 3+ orbits of commanding. In FSW 11.0 the sequence is complete in 6 minutes
- ***auto_sorce_orbit* powers on OBC if necessary, configures telecom system, loads special charge control sequence if necessary & clears watermarks**
- **The ground-generated stored command sequence (ATS) is loaded and started**
  - Loads state vector, commands SORCE to Normal Mode
  - Command to Normal Mode is attempted every 7 minutes throughout orbit day
  - When the S/C detects that it has been in normal mode for 5 minutes, it declares VICTORY (RTS 019) and enables the science sequences
  - Science observations initiated from ATS
  - Safing commands for TIM and XPS prior to S/C safing
- ***the_fixx* loops throughout the orbit**
  - Dumps event messages, monitors for safehold exit time, changes things not included in OBC FSW build (none currently)

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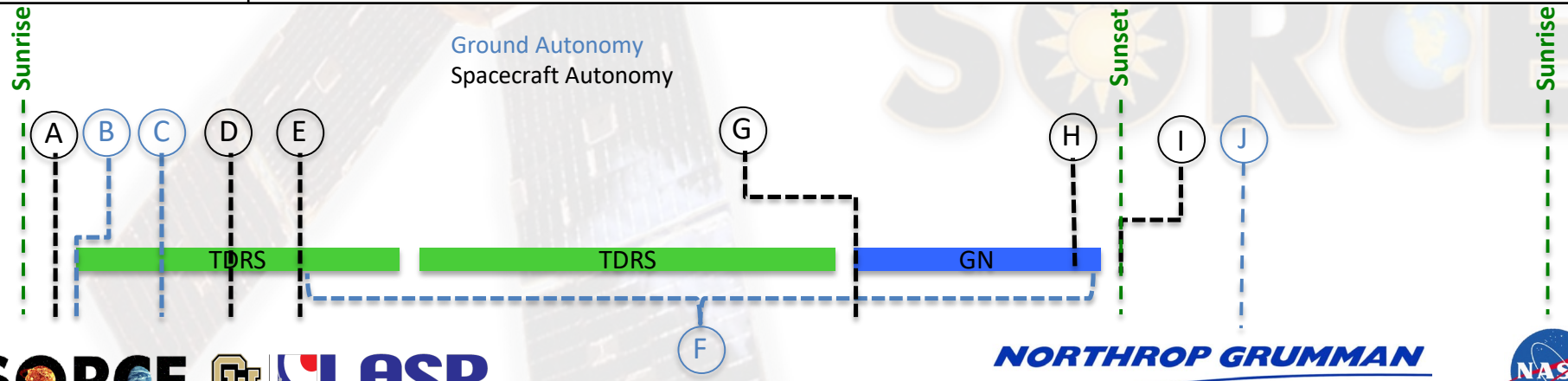
Orbit in the Life

Event	Details
A	Sun Rise + 60sec the APE turns on OBC, RWAs, Instruments, and TX, then begins transferring momentum from SORCE to RWAs
B	Sun Rise + 60sec first contact. ASO checks for brownout, backflips, low voltage, and general spacecraft health. **In the event of a brownout ASO will sync UL time with ground time**, turn on the OBC which will boot the APE to the most up to date software.
C	After ASO has declared the spacecraft in a safe configuration, an ATS is loaded to SORCE containing commands to normal and science for the orbit
D	TMON monitors for 60sec of SUNPOINT on the APE before starting the on board exit safehold sequence. Exit safe causes the OBC to regress to RATENULL. The on board sequence then quickly commands the OBC back to SUNPOINT.
E	ATS begins making attempts to normal mode (every 7min until 15min before eclipse entrance) followed by start instrument science sequence commands.
F	Ground Autonomy (the_fixx.prc) monitors for late start of exit safehold sequence and dumps event messages to real-time stream every 5min. Science is collected on real time stream during TDRS and through GN dumps when available
G	Higher AGC from a GN contact trips a TMON, starting 3 autonomous dumps of VR data
H	Eclipse -5min the ATS commands the observatory to safehold. This is to ensure that RWA1 is biased correctly at -60RPS before going into eclipse (momentum biasing)
I	At Sunset the APE detects <20A and turns off TX, OBC, RWAs, MU, etc. Momentum is dumped from RWAs to SC so that SORCE points at sun next sunrise even in the case of a brown out
J	ASO is started for the next orbit and the process starts all over again



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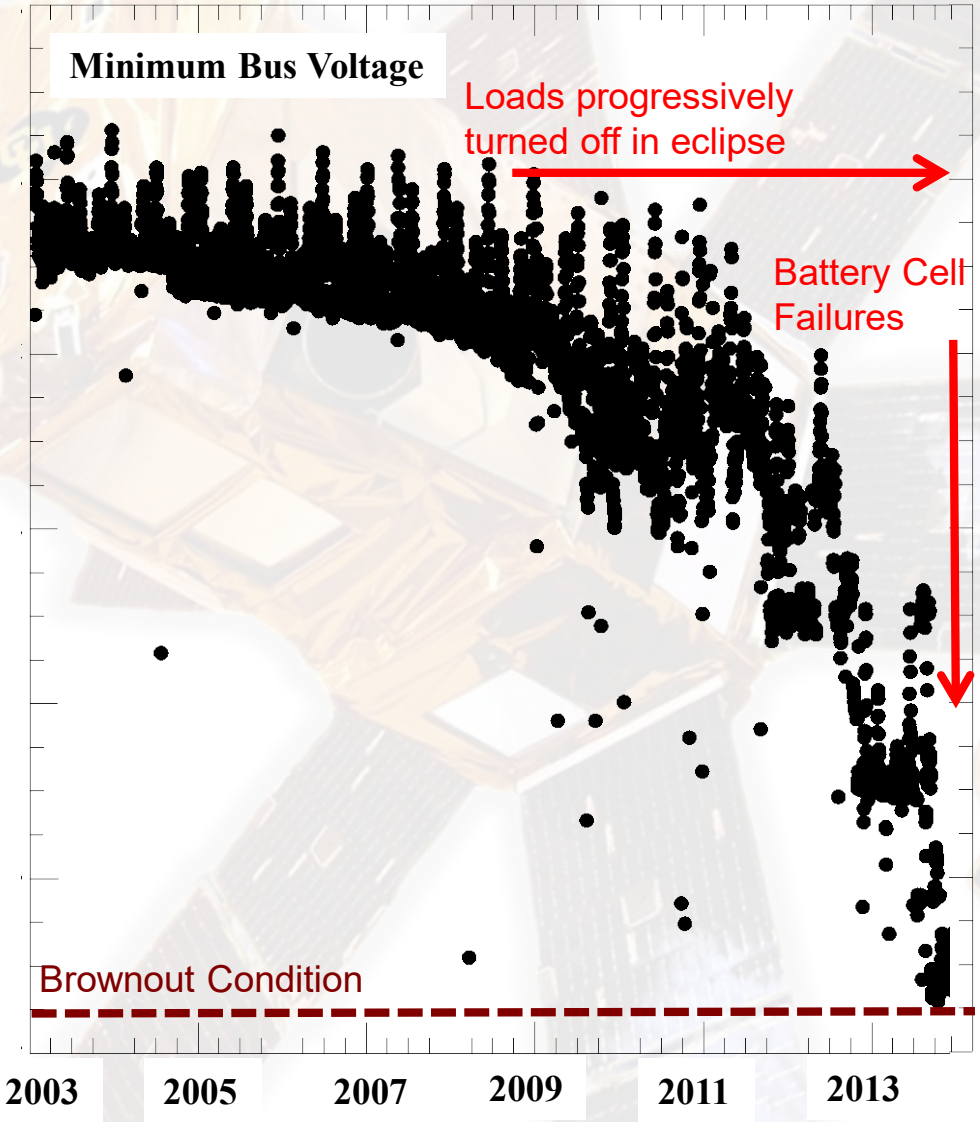
Daylight-Only Operations (DO-OP)

- **New ops concept of automated Daylight-Only Operations was activated in April 2014. This complete redesign of how the primary and backup computers were used on SORCE led to an entirely new ops concept that eliminated the need for a computer in eclipse. Many teams stepped up to make this happen including Orbital ATK, White Sands TDRS schedulers, SORCE scientists and the student operations team . Below are examples of work that went in to DO-OP:**

- **Flight Autonomy**
  - New FSW to configure the spacecraft for science every sunrise, make safe each sunset
- **Ground Autonomy**
  - Load products redesigned and process for developing and installing products reworked, new processes in place for ground system receipt of science data
- **Fault Protection**
  - Onboard telemetry monitoring system and ground fault monitoring and interaction completely reworked
- **Time**
  - Computer loses time each sunset, requiring jam commands to be sent each orbit
- **Science**
  - Relatively timed sequences designed and burned to spacecraft FSW that trigger science observations
- **Communication**
  - No information stored in SSR at sunset, motivated creative use of unused TDRS time to fill in orbits without ground contacts

Battery Challenges



- **In 2013, SORCE faced an uncertain future**
  - Minimum bus voltage was approaching the brownout threshold where the S/C could no longer support the primary computer in eclipse
- **July 2013 - Emergency Mode:**
  - Manual care of the spacecraft, commanding heaters each orbit and ensuring safe by sunset
  - 78 days of 24/7 operations
  - Momentum bias installed to prevent backflips
- **Led to the development of new automated ops concept…**