SOHO RECOVERY

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ABSTRACT

The Solar and Heliospheric Observatory (SOHO) is a joint program between the European Space Agency (ESA) and NASA. After a launch (by an Atlas IIAS rocket) on December 2 1995, SOHO was certified fully operational, at its vantage halo orbit around the first Lagrangian point, in April 1996. The instruments on-board SOHO brought a wealth of discoveries such as flows of gas inside the Sun; rivers of plasma beneath the surface of the sun; more than 50 sungrazing comets; spectacular images and movies of Coronal Mass Ejections which could allow to forecast space weather.

At the beginning of a 1-week long series of maneuvers, the control of the spacecraft was lost on June 25, 1998. Based on the last telemetry data received from SOHO, engineers had reasons to believe that the spacecraft was slowly spinning in such a way that its solar arrays do not receive adequate sunlight to generate power. However it appeared that SOHO's solar panels will be exposed to an increasing amount of sunlight each day as it orbits the Sun.

On July 23, the huge antenna of Arecibo confirmed SOHO spacecraft was at its predicted location and moreover than the spin rate was slower than 1 revolution per minute. On August 3, the spacecraft carrier was detected. As soon as one battery was charged up, a short burst of telemetry was collected on August 8.

The following challenge was to thaw the frozen hydrazine, starting with the tank, without discharging too much the batteries. When the tank was thawed after 11 days of heating, it appeared impossible to warm up the whole propulsion subsystem with heaters "digging into" the batteries during each eclipse period. Fortunately it was possible to patch the on-board software to use a solar array current like a “fake” thermistor, in order to switch ON heaters only when power was available from the solar arrays. This “sunheat” mode was used to increase the heating power without draining the batteries and had to be tuned several times to ensure the consumed power would stay within the available amount provided by the solar arrays. Such a tuning allowed us to put more and more heaters into “sunheat” mode and finally to thaw most of the propulsion subsystem.

On September 16, the spin rate was reduced by firing one of the thawed thruster and then a partial Emergency Sun Reacquisition successfully re-pointed the spacecraft, hence giving full power capability. Following a re-commission of the equipment and Station Keeping maneuver, SOHO was back into Normal Mode on Sept 25. Finally the instruments were tested and remarkably all work again correctly.

INTRODUCTION

The series of events that lead to loss of telemetry are presented in the SOHO Mission Interruption Final report (see Reference 1).
This paper is aimed at describing the recovery of the SOHO spacecraft, it covers mainly a 3-month period from June 25 to September 25 1998 when the attitude control was back to normal mode.
How telecommunications were reestablished with SOHO spacecraft is described in this paper, highlighting the involvement of engineers in Europe and at NASA GSFC, and also the support of the scientific community.
The long and careful thawing of the propulsion subsystem was a major challenge of the recovery and is sum up here after.
Using a solar array current like a "fake" thermistor is presented, including the different settings used before achieving a final "sunheat" power profile.
Finally the sun reacquisition maneuver is explained.

During normal operations SOHO always looks at the sun (X-axis), the two solar arrays give the Y-axis and the Z-axis is aligned with the poles of the sun. See SOHO spacecraft and axis given in figure 1. The two solar arrays always face the sun and can provide up to 1500 W. Power storage is ensured by two 20Ah NiCd batteries. In case of loss of sun pointing, an Emergency Sun Reacquisition (ESR) is triggered and then the Failure Detection Electronics (FDE) takes over with a hardwired attitude control using propulsion branch B thruster. The propulsion uses hydrazine as a mono-propellant with helium for pressurant. The eight 4N thrusters are used only during maneuvers (propulsion branch A) and in case of ESR (propulsion branch B).

SYMBOLS AND ABBREVIATIONS

ACS Attitude Control Subsystem
AGC Antenna Gain Control
AOCS Attitude and Orbit Control Subsystem
BCR Battery Charge Regulator
BDR Battery Discharge Regulator
COBS Central On-Board Software
DSN Deep Space Network
EOC End Of Charge
ESA European Space Agency
ESR Emergency Sun Reacquisition
FDE Failure Detection Electronics
FOT Flight Operations Team
GSFC Goddard Space Flight Center
ISA Initial Sun Acquisition
LGA Low Gain Antenna
SAS Sun Acquisition Sensor
SOHO Solar and Heliospheric Observatory

GETTING BACK TELEMETRY

Assessment of SOHO status at the loss of telemetry

Owing to Single Event Upsets a built-in protection had switched OFF 3 out of 4 Battery Discharge Regulators (BDR), therefore only one battery was connected to the power bus, which limited the spacecraft autonomy in the case of loss of sun pointing. Without enough power available, the equipment, heaters and instruments were automatically switched OFF. The hydrazine in the tank (about 180 kg) began to cool down and then to freeze slowly.

The spacecraft was already in a "communications backup" configuration: each of the two transponders connected to a Low Gain Antenna: receiver 1 to LGA+Z, receiver 2 to LGA-Z. Since April 1997, receiver 1 is impaired and can be locked only by a slow frequency sweeping. Since this anomaly the lock frequencies of both receivers are not the same.

After the loss of attitude control and telemetry several attempts were made to reestablish communications, including commands to reconnect one battery to the power bus. Owing to the loss of the sun pointing and hence to the onboard power outage, these first sequences were not successful.

At the time of the loss of contact, SOHO was spiraling off the sun with a spin rate (around its X axis, 2000 kgm2 of inertia) estimated to be six to eight degree/second. Flight dynamics analysis and simulation showed that the spacecraft would be spinning around its major inertia axis (Z axis, 3600 kgm2 of inertia) after some time. By the end of June, SOHO would have its solar arrays edge on to the sun. The motion around the sun degree by degree, day after day, increases the period with sunlight impacting on the solar arrays. It means that after 3 months the Z axis would become perpendicular to the sun, which would bring light into the solar arrays and hence power to the spacecraft (see figure 2).

Whether the +Z or the -Z axis would be facing the sun was not known at the beginning of the recovery. On this assumption several thermal simulations were run:

- “Plus Z”: +Z axis facing the sun, no power available (hence not possible to get telemetry).
- “Plus Z at 45 degrees”: same as above but with +Z axis at 45 degrees of the sun, in such a case there will be some power available, the good receiver (receiver 2) in visibility of the earth and telemetry equipment rather cold (from -10 to -30 C). This might (and in fact did) occur 46 days after ESR-7.
- "Minus Z": -Z axis facing the sun, no power available.
- "Plus Y": Z axis at 90 degrees of the sun which gives full power over half the time.

Overall it appeared possible to reestablish communications with SOHO within six to eight weeks.

According to Flight Dynamics, SOHO would stay on its halo orbit (around L1 point) and diverge only slowly up to mid-November 1998, after that, the orbit would diverge and the spacecraft would have escaped into a solar orbit.

Detection of the downlink carrier

In order to get a "spike" of the downlink carrier, two recovery sequences were defined (new operational procedures). They had to be as short as possible because power was available only for a limited period of time (estimated to be less than 20 seconds). One sequence was to set relays in the Data Handling and for the power supply, which was done by sending decoder commands. The decoders are powered through safe lines as soon as there is power available onboard. The second sequence was to switch ON the data handling and then the transmitter without modulation. These procedures were repeatable and sent either through receiver 1 or through receiver 2 (hence at different frequencies and using several sweeping profiles and rates).

Meanwhile a spectrum analyzer had been installed at DSN station in order to detect any spike of the downlink carrier. Actually many spikes were detected and appeared to be induced by radio interferences, even out of commanding period. Beginning July 1, ESA ground stations, in Australia, Spain, South America and Belgium, reinforced the sky watch to search for the SOHO carrier signal. Spectrum analyzer settings were coordinated between ESA and DSN, measurement results processed and communicated to the FOT at GSFC.

Following a proposition by researchers at the US National Astronomy and Ionosphere Center, on July 23 the 305-m antenna of Arecibo radio telescope (Puerto Rico)was used to perform a bistatic radar test (with a power of 580kW transmitting at 2.380 GHz). This was successful: a 70-m station at Goldstone was able to receive strong echos from SOHO at its predicted location. Moreover the signal width was between 1 to 2 Hz, which is compatible with a spin rate of 53 seconds (determined through Fourier analysis by radar experts at Cornell University). The center frequency drifted slowly by a few Hz indicating a non-principal axis of rotation. Besides an analysis of the collected data indicated a radar cross section of 15 to 20 m*m, compatible with SOHO dimensions. All this gave great hope to recover SOHO.

On August 3 (the 40th day after the loss of contact), the recovery sequence to switch ON the downlink carrier was updated to contain fewer commands (for instance the battery management was taken out) and to add delays between decoder commands. It was sent successfully to receiver 2 (connected to LGA-Z): spikes of the downlink carrier were detected (lasting 2 to 10 seconds, both received by Goldstone and by ESA Perth stations, at 2244.945 Mhz, with a ground AGC of –135 dB).

The carrier was switched ON for increasing period of time (up to 60 seconds). Several times the ground station was able to lock but the duration was still too short to decode the telemetry data. During a test to switch ON transmitter 1, no signal was detected on the ground; which means that the LGA+Z was still not visible from the earth (this fits the case "Plus Z at 45").

Charge of the batteries and first frames of telemetry

Several attempts to charge a battery and to connect it to the bus were not successful. Investigation by battery experts in Europe showed that below 20 Volts, there wouldn't be enough power to maintain the Battery Charge Regulator ON. Therefore to charge one battery it was necessary to keep sending the BCR ON command. On August 8, after 10 hours of such an in-loop commanding, battery 2 was charged up and successfully connected to the bus to get telemetry. To avoid discharging the battery, its two Battery Discharge Regulators (BDR) were opened at the end of the test, which switched OFF the power and hence the transmitter.

These first frames of telemetry confirmed the extreme temperatures, for instance: batteries at -20 C, gyros at about -25 C, some instruments very hot (+80 C) others very cold (-60 C). With the batteries so cold and to avoid any overcharge, the automatic temperature dependent control of the End Of Charge was disabled.

Analysis of the Sun Acquisition Sensor data confirmed a rotation period of 52.6 seconds and that +Z was facing the sun. This also determined the angle from rotation axis to the sun (about 36.7 degrees, measured on August 11).

THAWING THE PROPULSION SUBSYSTEM

Thawing the tank

A new power budget was built based on the power consumption the equipment needed for the coming operations as well as the ratio between charge and discharge of the batteries. Owing to the rotation period, the batteries were in charge only 45% of the time (with a 1A charge current for each battery). This power budget showed that the batteries would charge over several periods if the total power consumption stayed below 67 Watts. In fact to switch telemetry ON consumes 105 W and hence induces a drain of the batteries. Obviously the batteries would have to be charged up each time their voltages will reached a limit, set between 40 and 41 V.

When telemetry was recovered (August 8) the propulsion subsystem was very cold: tank partially frozen (at ~ 1 C), one pipe at -16 C, several thruster as cold as -35 C.
The propulsion experts wisely established that the thawing of the hydrazine must be done first for the tank, then for the pipe section 4 which contains the latch valves. Since latch valve B was open (propulsion branch B used in ESR) it will be closed to cope with any leakage downstream. Then the rest of the pipes sections 1, 3 and then 2 and finally the thruster will be thawed. Doing so will allow any overpressure of thawed hydrazine to flow back to the tank through liquid lines.

On August 12, the nominal and redundant tank heaters were switched ON (total of 32 W). The tank heating was performed with both batteries providing power only to the tank heaters. All the other equipment were switched OFF except for short telemetry checks (temperatures and batteries voltage) every 4 hours. It was necessary to interrupt three times the tank thawing process to recharge the batteries. The total consumed power during heating was about 87W (with telemetry OFF). On the plots of the battery voltages during the whole recovery (in figure 3), one can see the periods of heating and battery charging (which had to be tuned several times after long lively debates between the propulsion/thermal and power experts of the recovery team).

Thawing the tank was achieved (on August 30) after 275 hours of heating (more than 11 days, without taking into account the battery charge periods). It was longer than expected (7 days) owing to higher than estimated heat losses during the interruption of the thawing (to charge the batteries) and also to a more important mass of frozen hydrazine. The tank temperatures given in figure 4 show the slow thawing of the hydrazine.

The "sunheat" mode

It appeared impossible to warm up the whole propulsion subsystem with heaters "digging into" the batteries during each eclipse period. The batteries charge with a 1A current. When telemetry is ON, the power consumption is 105W, which, during each eclipse period, discharge the batteries with a current of 1.25A. To recover SOHO there was a crucial need of switching ON more heaters and equipment without draining the batteries.

Fortunately it was possible to patch the Central On-Board Software (COBS) to use a current like a “fake thermistor” in order to switch ON heaters when power was available from the solar arrays and OFF if not. In a thermostatic regulation, COBS reads a thermistor value and switches a predefined heater OFF when above a "maximum" threshold and ON when below a "minimum" threshold. This was inverted and extended at switching ON a heater when a solar array current was above a "maximum" and OFF when below a "minimum".
Such a patch consisted of changing the following tables (no patch of the code):

- the one defining which thermistor to be used for each thermal control circuit,
- the heaters table to allow to switch ON at the same time both the nominal AND the redundant heaters of the same circuit,
- the memory location of the thermistors.

This patch was first tested on August 19. It had to be reloaded after each battery charging period (during charge the on-board computer is OFF). It is also referred as the “sunheat” mode, which allowed increasing the heating power without discharging the batteries.

First the “solar array current” was used like a fake thermistor which worked perfectly but the power experts thought the heating power would be reduced due to a shadowing effect of the spacecraft body on one of the two solar arrays (this was called the "shunt" mode). Then the charge current of one battery was used instead (referred as "charge" mode). On the other hand as soon as they was enough power available the battery charge current increased from 0 to 1A, therefore the sunheat was active as long as the battery was in charge, sometimes even longer which did drain the batteries a bit. Moreover it was not possible to switch ON more than 150W in “sunheat” mode because this would at once discharge the batteries and hence switch OFF the heaters in "sunheat" mode. These two "sunheat" profiles are given on the top part of figure 5, over the non-eclipse time of each period (when solar arrays in sunlight).

On September 4 a mixed solution was selected:

- the most important heaters for warming up the propulsion were put in “charge” mode (using the battery charge current for the "sunheat" mode) to ensure an equivalent 40% duty cycle of heating;
- other heaters were switched ON few seconds later and switched OFF earlier this was done by using again the solar array current like a fake thermistor ("shunt" mode).

Since this strategy worked well to heat up without discharging the batteries, it was used for more heaters. Overall it consisted of defining a heating power profile that will always be within the amount available from the solar arrays. At the end 48 heaters were put in “sunheat” mode for a total of 517W of heating power. See the "final sunheat" profile on figure 5.

Thawing pipes and heating thrusters

The pipe section 4 was the first one to be thawed, it contains the latch valves and pressure transducers. On figure 4 one can see the increase of temperature and pressure in pipe 4 during its thawing. Pipe 4 was considered thawed on Sept 1; then Latch Valve B was closed (see the increase of branch B pressure up to the back pressure relief level of the valve). Then pipes 1, 3 and 2 thawing were completed on Sept 3.

The propulsion subsystem was kept warm by heating/charging cycles, this done until the final attitude recovery maneuver. Nevertheless it was believed that the thrusters in the spacecraft shadow were not completely thawed (thruster 7B and 8B).

ATTITUDE RECOVERY MANEUVER

Four solutions

Several attitude recovery maneuver were studied:
- ESR without roll control, hence without using thrusters 5B, 6B, 7B and 8B (this solution was the one finally selected mainly because thrusters 7B and 8B were still cold before the maneuver);
- Full ESR recovery which would have used all the thrusters of propulsion branch B;
- Dual spin (in which the spacecraft would have been stabilized around its minimum moment of inertia);
- ISA (Initial Sun Acquisition) recovery, in fact this approach would have used propulsion branch A (in case B side not available).

The maneuver

The recovery maneuver was executed on September 16 with the following steps:
- full battery charge and then a 6-hour heating boost of the propulsion subsystem,
- upload of new onboard standard monitoring to be used to trigger ESR when spacecraft pointing towards the sun,
- test of thruster of branch B, fired for 3 seconds (except 7B and 8B),
- calibration and despin with thruster 4B (down to 0.86 deg/s),
- ESR triggered and sun reacquisition achieved,
- Go back to normal settings of the thermal control.

The gyros were not used for the partial ESR. In fact the roll rate was corrected using thruster 5B or 6B in open-loop from the ground. In ESR, the roll rate was less than 0.2 degree/s, measured through gyro B output and also through analysis of SAS 1B data (a Lissajou plot of pitch and yaw angles gives the sign and the magnitude of the roll rate).

Spacecraft and instruments status at the end of the recovery

Owing to the extreme cold conditions two gyros appeared to be not usable (gyros A and C). Except for these two gyros, all the spacecraft equipment began to work again correctly.
The instruments were checked out between October 5 and 24, remarkably all performed as well as before the mission interruption, some even better.

CONCLUSION AND EPILOGUE

More than 160 members of the SOHO recovery team (ESA, MMS, NASA, ATSC) have performed outstanding work and found imaginative solutions.
On December 21 1998, the third and last gyro was lost, which put SOHO into ESR mode.
With new solutions to:

- reduce the orbit perturbation of the ESR mode (by manual yaw braking from the ground),
- accurately measure the roll rate (wheels spun-up so that there is a net momentum on pitch, which combined with the roll rate creates a yaw disturbance torque),
- patch the Attitude Control Software to fly SOHO without gyro control,
- implement new or updated procedures, including the one to recover from ESR (now done without gyroscope control),

SOHO spacecraft was put back into normal mode on February 1, 1999.
Since then it is the first three-axis-stabilized ESA spacecraft to be operated without a gyro.

REFERENCES

R1 SOHO Mission interruption joint NASA/ESA Investigation board
R2 The SOHO Recovery, on the web at:
http://sohowww.nascom.nasa.gov/operations/Recovery/

TABLES

Events

Date	Time UT	Events
25-Jun-98	04:38	EMERGENCY SUN REACQUISITION (ESR-7)
25-Jun-98	04:43	Interruption of Mission
23-Jul-98	10:00	Confirmation of Orbit Position and Spacecraft Spin Rate by Arecibo and DSN Radar
3-Aug-98	22:51	Reception of Spacecraft Carrier Signal by DSN
8-Aug-98	23:14	Successful battery charge Reception of Spacecraft Telemetry
12-Aug-98	23:39	Begin Thawing of Hydrazine Tank
28-Aug-98	23:02	End thawing of Hydrazine Tank (degrees)
30-Aug-98		Begin Thawing of Hydrazine Lines
16-Sep-98	05:45	Start of Attitude Recovery
16-Sep-98	18:29	ESR 8
16-Sep-98	18:30	SOHO lock to Sun
21-Sep-98	16:58	SOHO in RMW
25-Sep-98	17:30	Orbit Correction (first segment)
25-Sep-98	19:52	SOHO in Normal Mode
Oct 5 to 23		Instruments re-commissioning

FIGURES

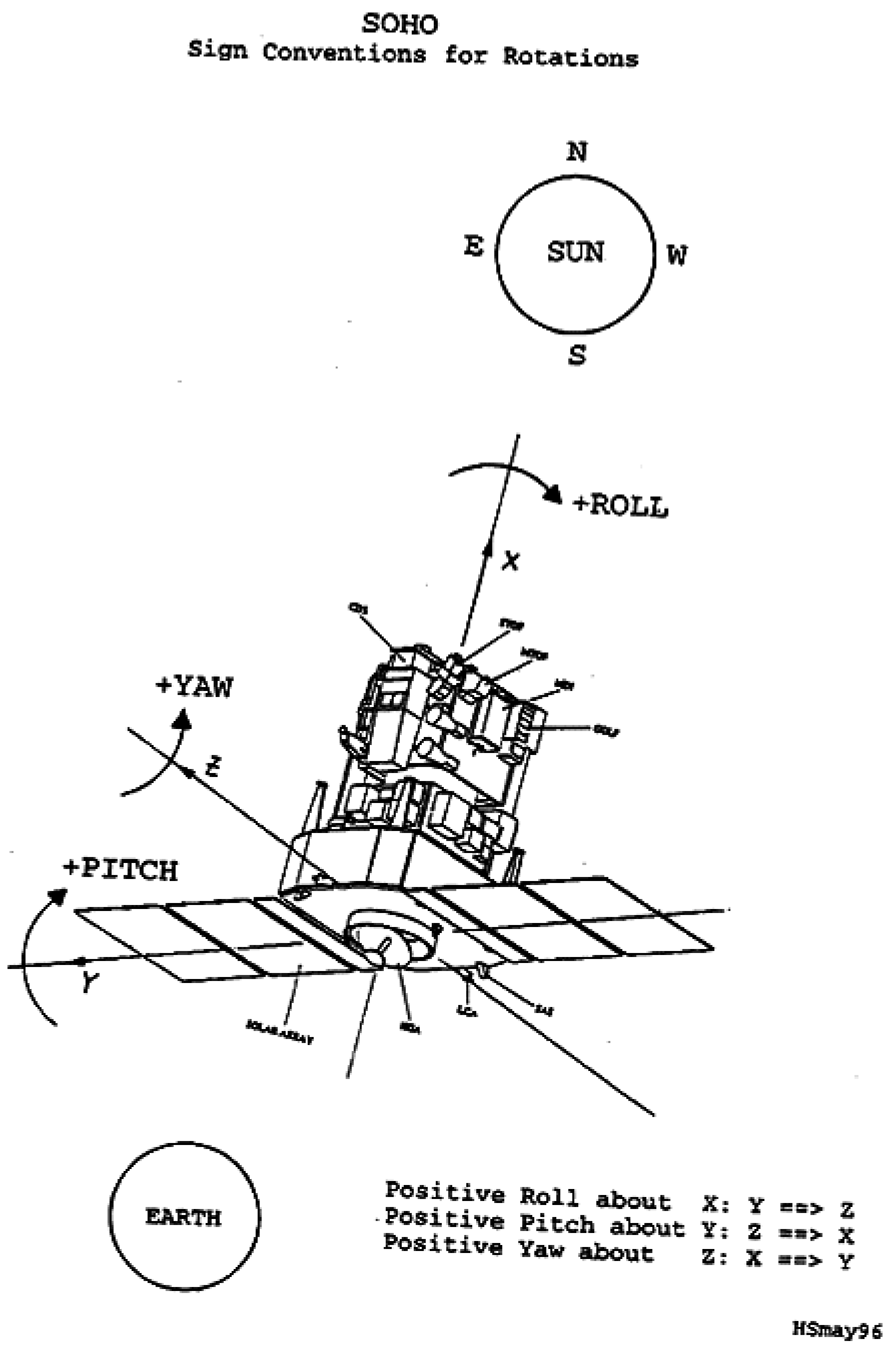


Figure 1: SOHO overview and axis conventions

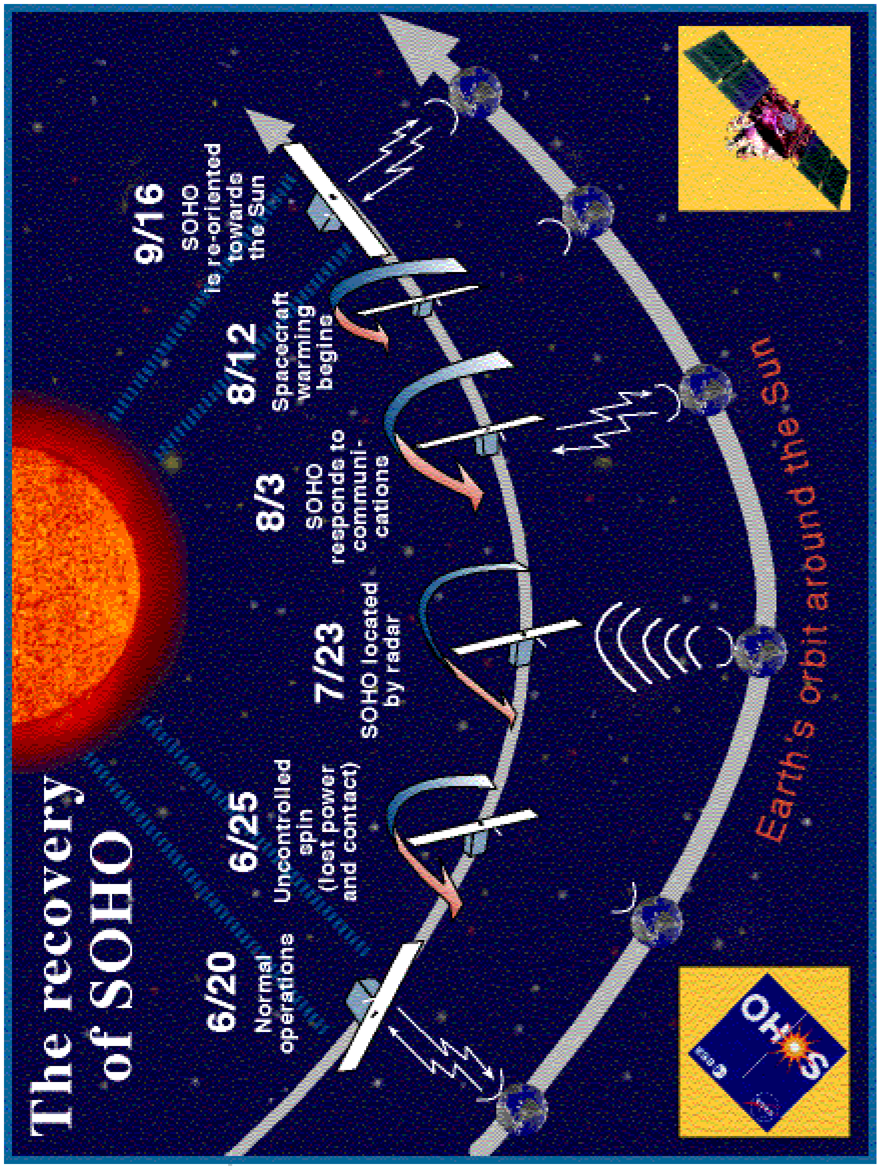


Figure 2: SOHO recovery phases

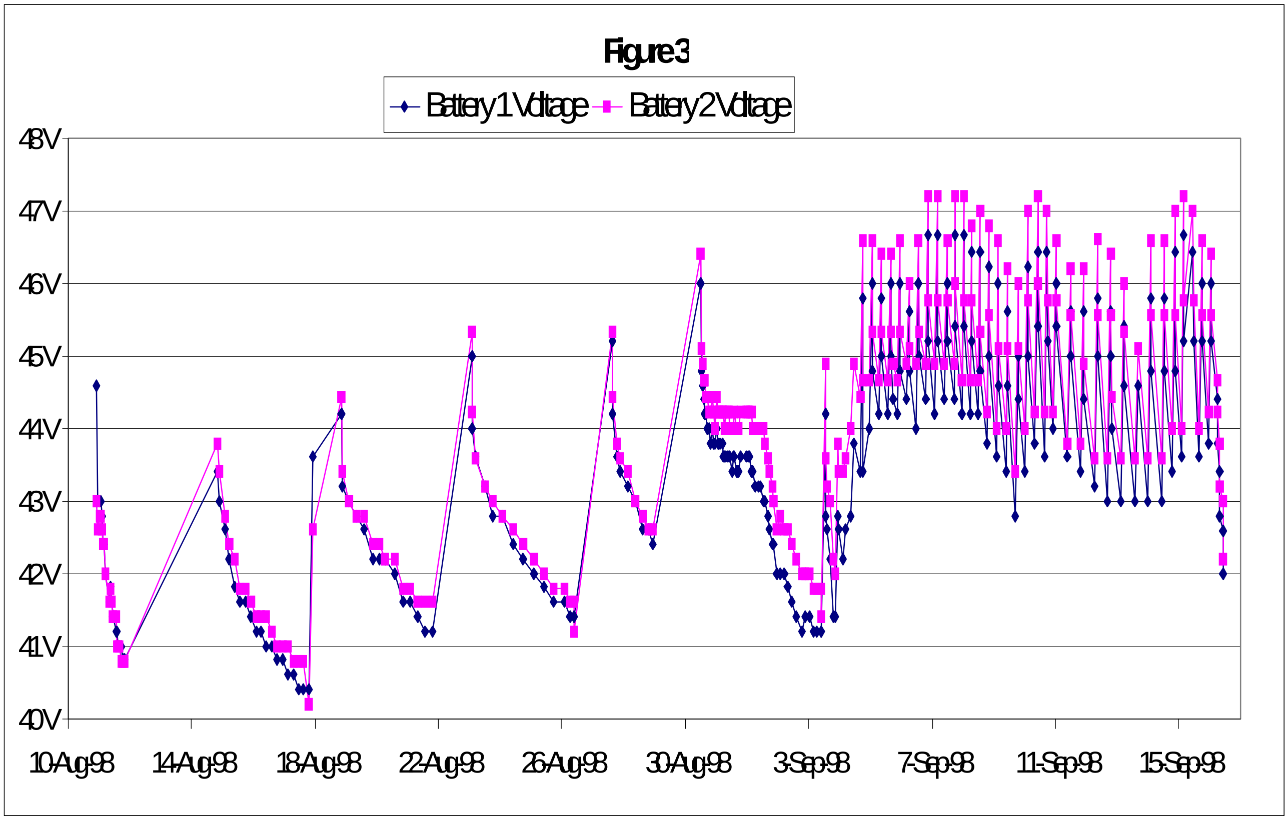
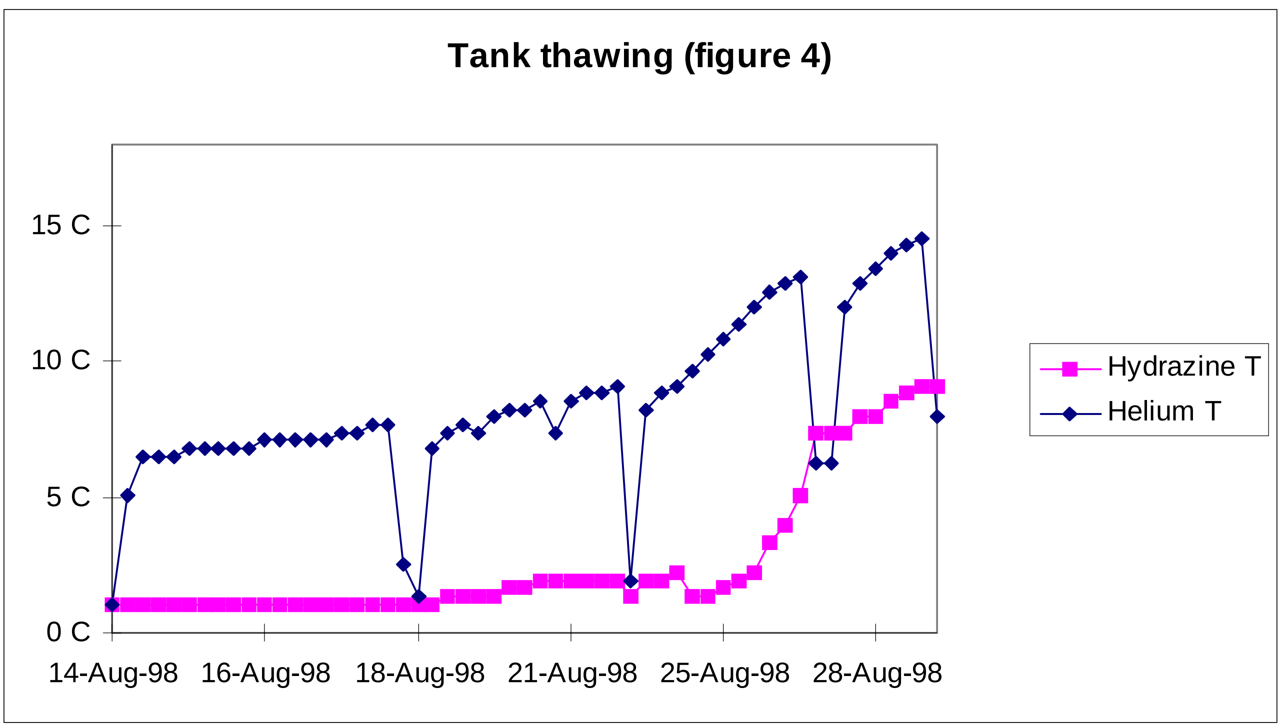
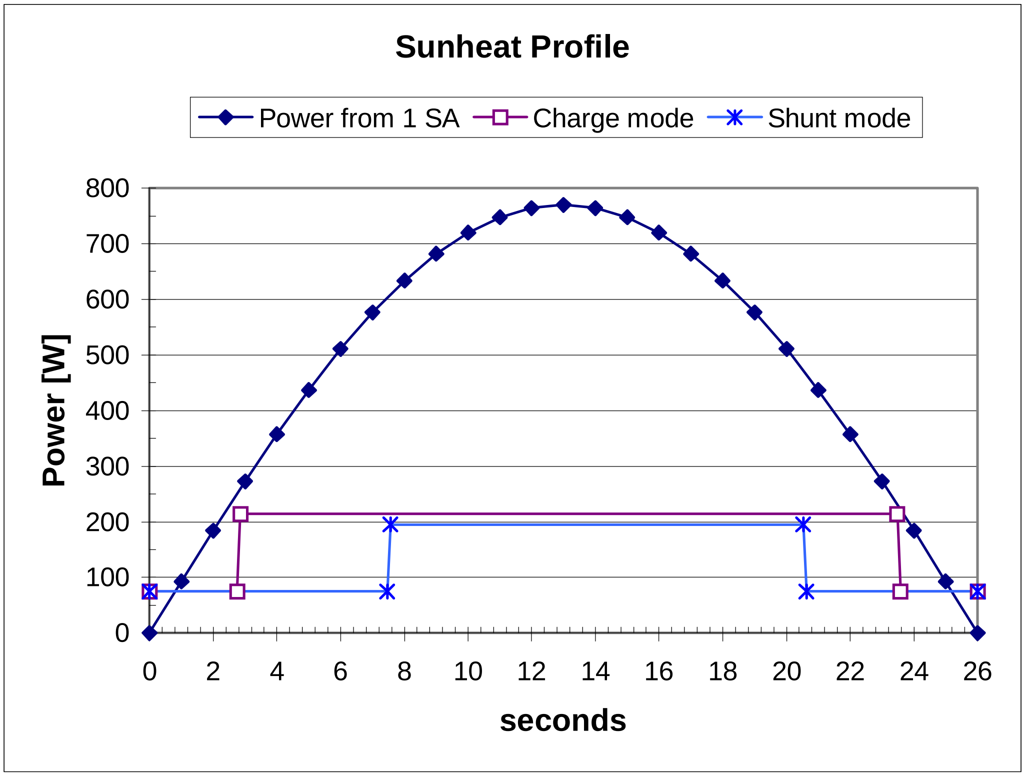


Figure 3
Battery 1 Voltage
Battery 2 Voltage
48V
47V
46V
45V
44V
43V
42V
41V
40V
10-Aug-98
14-Aug-98
18-Aug-98
22-Aug-98
26-Aug-98
30-Aug-98
3-Sep-98
7-Sep-98
11-Sep-98
15-Sep-98



Tank thawing (figure 4)
15 C
10 C
5 C
0 C
14-Aug-98
16-Aug-98
18-Aug-98
21-Aug-98
25-Aug-98
28-Aug-98
Hydrazine T
Helium T



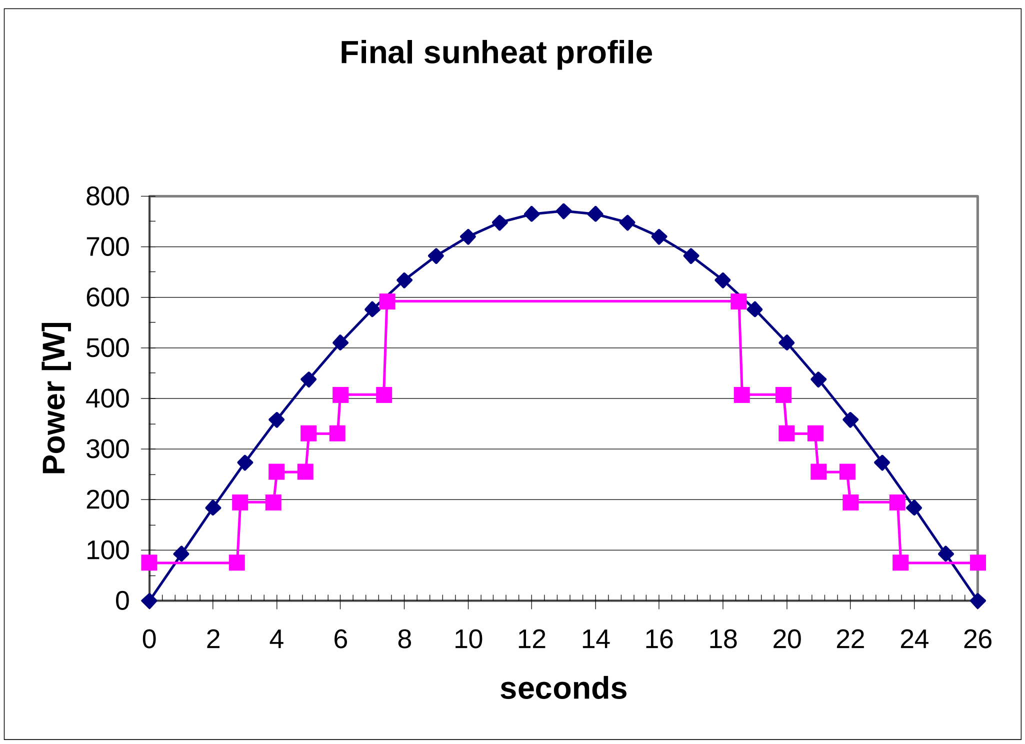
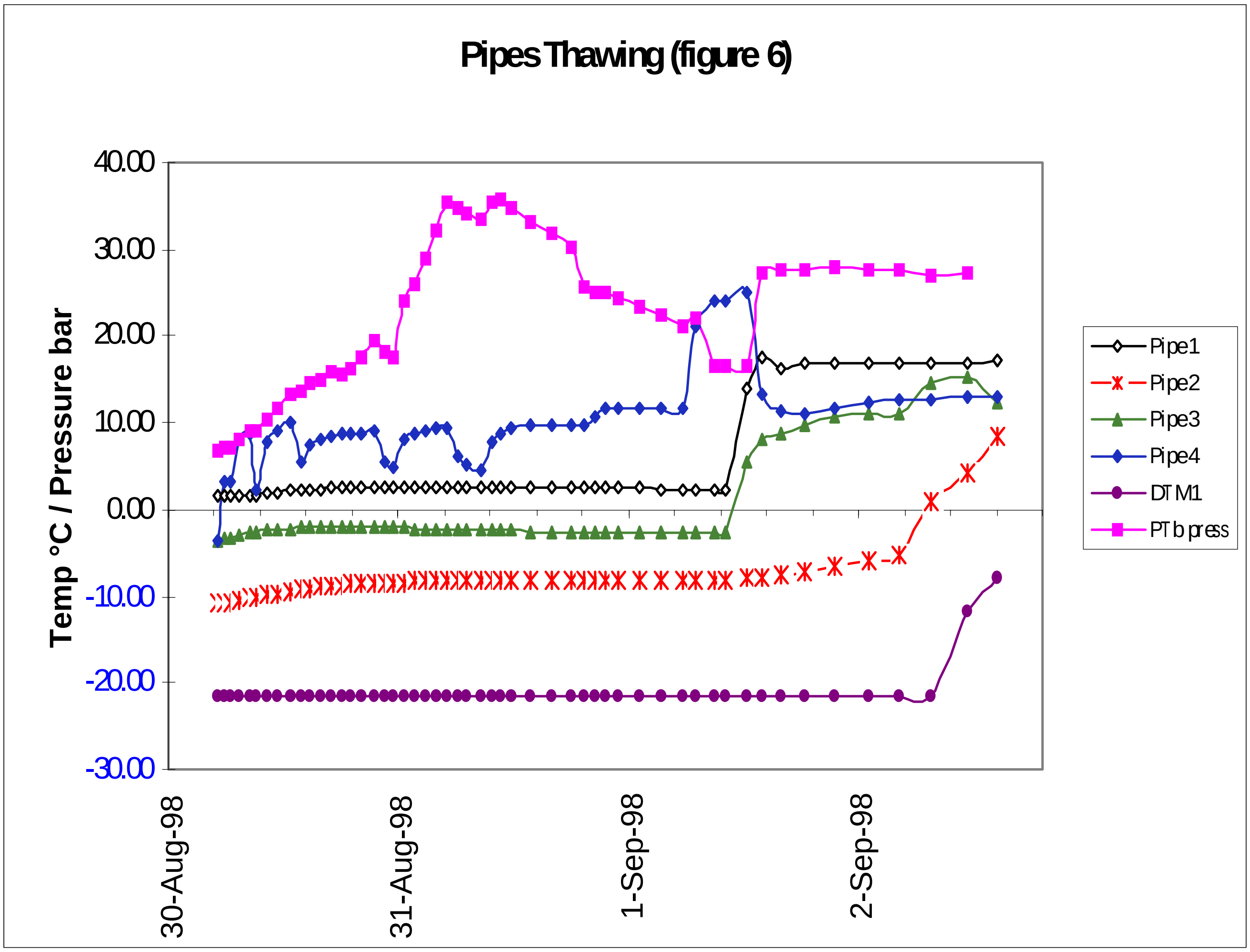


Figure 5: "Sunheat" profiles when solar arrays in sunlight



Pipes Thawing (figure 6)
Temp °C / Pressure bar
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
30-Aug-98
31-Aug-98
1-Sep-98
2-Sep-98
Pipe1
Pipe2
Pipe3
Pipe4
DTM1
PTb press