Exp Astron (2014) 37:397–431
DOI 10.1007/s10686-014-9388-z

ORIGINAL ARTICLE

Operations and performance of the PACS instrument ^{3}He sorption cooler on board of the *Herschel* space observatory

M. Sauvage · K. Okumura · U. Klaas · Th. Müller · A. Moór · A. Poglitsch · H. Feuchtgruber · L. Duband

Received: 16 November 2013 / Accepted: 8 April 2014 / Published online: 9 May 2014

Abstract A ^{3}He sorption cooler produced the operational temperature of 285 mK for the bolometer arrays of the Photodetector Array Camera and Spectrometer (PACS) instrument of the *Herschel* Space Observatory. This cooler provided a stable hold time between 60 and 73 h, depending on the operational conditions of the instrument. The respective hold time could be determined by a simple functional relation established early on in the mission and reliably applied by the scientific mission planning for the entire mission. After exhaustion of the liquid ^{3}He due to the heat input by the detector arrays, the cooler was recycled for the next operational period following a well established automatic procedure. We give an overview of the cooler operations and performance over the entire mission and distinguishing in-between

Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

M. Sauvage (✉) · K. Okumura
Commissariat à l'Energie Atomique, IRFU, Orme des Merisiers, Bât. 709, 91191 Gif/Yvette, France
e-mail: marc.sauvage@cea.fr

U. Klaas
Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

Th. Müller · A. Poglitsch · H. Feuchtgruber
Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße, 85748 Garching, Germany

A. Moór
Konkoly Observatory, MTA CSFK, Konkoly Thege Miklós, út 15-17, 1121 Budapest, Hungary

L. Duband
Commissariat à l'Energie Atomique, INAC, Service des Basses Températures, 17, rue des Martyrs, 38054 Grenoble, France

the start conditions for the cooler recycling and the two main modes of PACS photometer operations. As a spin-off, the cooler recycling temperature effects on the *Herschel* cryostat ^{4}He bath were utilized as an alternative method to dedicated Direct Liquid Helium Content Measurements in determining the lifetime of the liquid Helium coolant.

Keywords Herschel · PACS · SPIRE · Telescopes · Space vehicles: instrumentation · Instrumentation: Photometers · Calibration · Space cryogenics · Sorption coolers · ^{3}He system

1 Introduction

The *Herschel* Space Observatory [8] with its 3.5 m telescope provided an excellent platform for FIR observations with unprecedented sensitivity, photometric accuracy and spatial resolution. The FIR instrument PACS [9] employed the largest detector arrays [2] ever flown in space. Its bolometer arrays needed to be cooled to an operational temperature of 285 mK, which was achieved by means of a ^{3}He sorption cooler inside the instrument. We give a short overview of this type of device, which was also used for the SPIRE [5] instrument, the recycling process and the characterization of the cooler hold time, which was an essential parameter for the *Herschel* scientific mission planning. We present a statistics and characteristics of all PACS cooler cycles over the entire *Herschel* mission. Finally we sketch a method utilizing the thermal interaction of the sorption cooler pump and the ^{4}He coolant in the *Herschel* cryostat, by dumping a constant heat input, for determining the remaining liquid ^{4}He mass and hence its lifetime.

2 The PACS ^{3}He sorption cooler

The *Herschel* flight model cooler is described in detail in [4]. Figure 1 gives a 3D view of the device showing its main components.

The evaporator contains a porous material, an alumina sponge (91 % Al_2O_3 / 9 % SiO_2), which traps the liquid ^{3}He during the cold state. This liquid ^{3}He evaporates providing the cooling to the detector focal plane. When all the liquid ^{3}He has been evaporated into the gas phase, it needs to be recycled. The gaseous ^{3}He flows into the sorption pump which contains active *charcoal* for adsorption of the gas.

3 Procedure of the cooler recycling

Figure 2 provides a schematic view of the PACS cooler elements and their thermal connection to the bolometer detector focal plane unit and the liquid ^{4}He bath of the *Herschel* cryostat, also referred to as the level 0 of the thermal system, L0, at ≈1.7 K.

Figure 3 shows the evolution of the temperatures relevant for the cooler during the different steps of the recycling process as monitored via Housekeeping (HK)

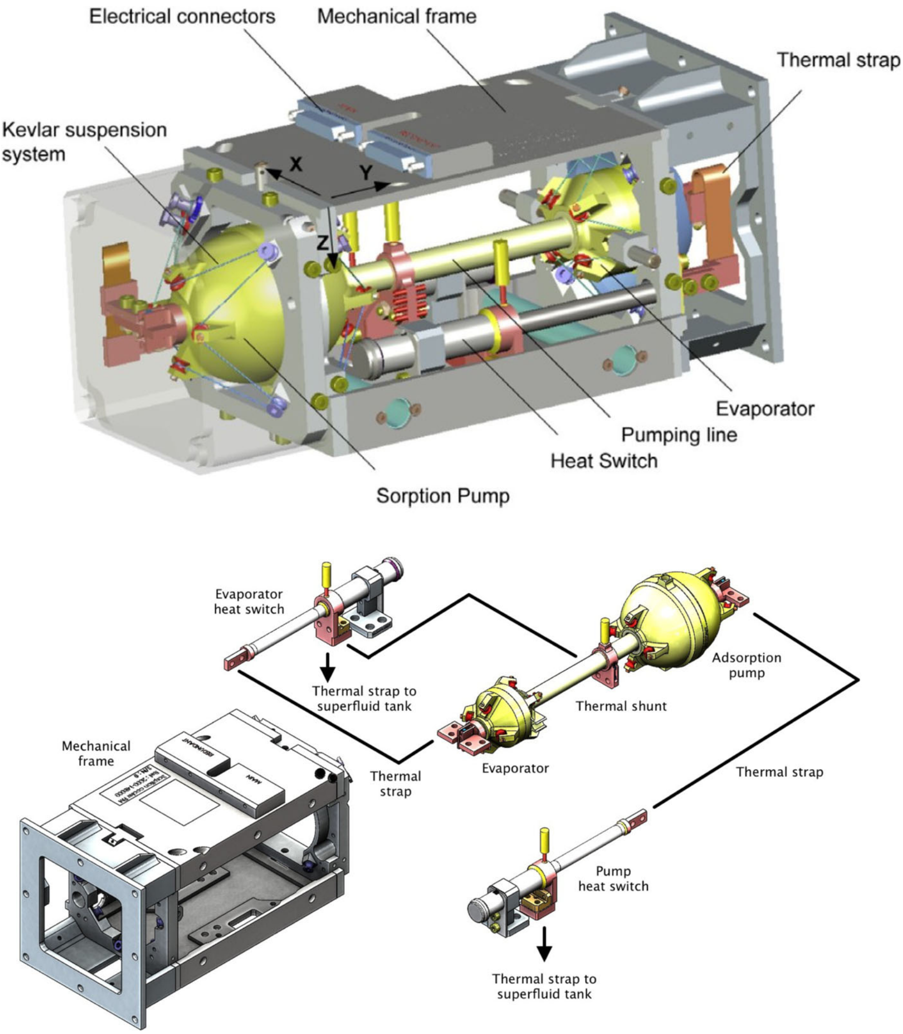

Fig. 1 Overall 3D views of the PACS cooler identifying its main components from [4]. The *bottom* figure presents an exploded view identifying the elements represented schematically in Fig. 2

parameters from temperature sensors. At the beginning, the evaporator temperature (TEMP_EV) is around 2 K indicating that the cooler has run out of liquid coolant. The recycling procedure is completely controlled via heaters and heat switches integrated in the cooler. The heat switches are of the gas-gap type, where the presence or absence of gas between two interlocked copper parts changes drastically the heat flow between them. Gas handling is achieved with a miniature cryogenic adsorption pump [3].

The first 15 minutes serve to settle the thermal environment. The pump heat switch HSP in Fig. 2 has to be open, so that the pump does not dissipate heat into the

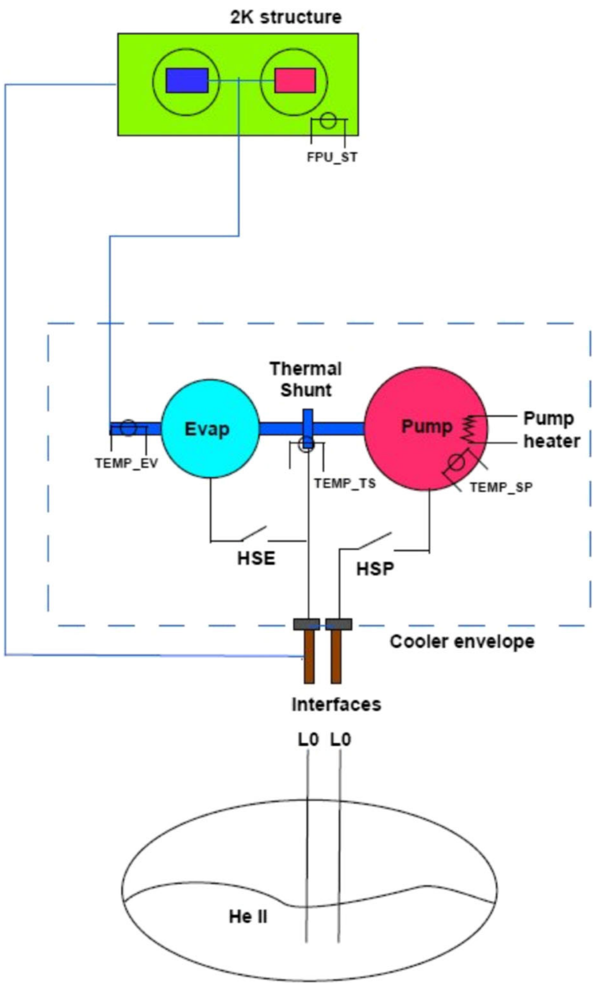

Fig. 2 Schematic drawing of the PACS cooler elements and the thermal connections to the PACS bolometer detector focal plane unit (in *green*) and the liquid ^{4}He L0 bath of the Herschel cryostat at ≈1.7 K

instrument. The evaporator heat switch HSE in Fig. 2 is closed so that the evaporator thermalizes with the 2 K level and does not warm up too much when the pump is heated and thus still traps condensing gas. The heat switches HSP and HSE are closed by applying a current and opened by setting the current to zero.

The recycling proper starts with heating the sorption pump (SP) to desorb the gas that has been trapped in the active charcoal. After 35 min the heater current is lowered to keep the pump at the required temperature of about 40 K. At this time ^{3}He outgases from the pump and condenses. TEMP_EV rises following the temperature rise of the pump both because the enthalpy of the hot gas coming from the pump is not fully removed by the thermal shunt and due to the latent heat of ^{3}He. Since the evaporator and the shunt are connected to the same thermal strap, all variations happening at the shunt are also registered by the evaporator temperature sensor (TEMP_EV).

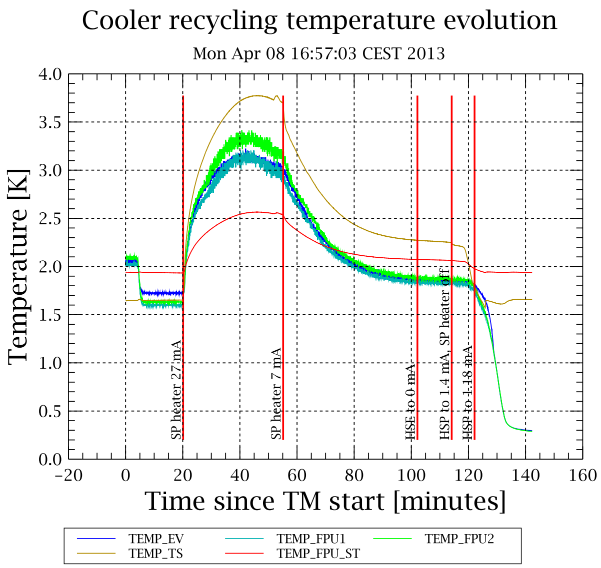

Fig. 3 Evolution of temperatures relevant for the PACS cooler monitored by sensors and provided in the PACS instrument Housekeeping (HK) during the cooler recycling process

TEMP_EV decreases when the pump is kept at the required temperature. At around 80 min TEMP_EV drops below the 2 K level. The finally achieved TEMP_EV in this step characterizes the efficiency of the recycling.

After 82 min the evaporator heat switch HSE in Fig. 2 is opened $HSE = 0\,mA$ to thermally isolate the evaporator. To establish the cooling functionality the pump heater is switched off after 94 min and the pump is re-connected to the 2 K level by closing the pump switch HSP in Fig. 2. Once the pump is connected to the 2 K level the charcoal in the pump starts pumping and the ^{3}He pressure drops. The thermally insulated liquid ^{3}He decreases in temperature to below the 300 mK level which is reached after around 142 min.

The cooler recycling procedure with the tuned time steps as described above proceeded fully automatically. The duration of the PACS-only cooler recycling block was 142.37 min, the duration of the parallel mode cooler recycling block 172.53 min. This automatic cooler recycling procedure implemented by means of the *Herschel* Common Uplink System (CUS) is documented in the online Appendix.

4 Establishment of the cooler hold time relation for *Herschel* mission planning

The *Herschel* Space Observatory executed its observations autonomously along a Mission Timeline (MTL) stored on-board, while ground contact was only during the normally 3 h long Daily Telecommunication Period (DTCP). The mission was divided into Operational Days (ODs) of on average approximately 24 h duration, each beginning with a DTCP during which the MTL for a forth-coming OD was uploaded. This pre-planned automatic command execution without the possibility of human intervention meant that a reliable prediction of the cooler hold time for PACS photometer operations was necessary. The cooler hold time was defined as the period between TEMP_EV going below 300 mK at the end of the recycling process (cf. Section 3 and Fig. 3) and TEMP_EV exceeding 320 mK when liquid Helium in the cooler was exhausted.

The essential parameter determining the length of the cooler hold time was the time when the PACS bolometer detectors were biased for measurement. This period was set by the so-called orbit prologue and orbit epilogue, engineering-type Astronomical Observations Requests (AORs) setting and resetting the detector bias and bracketing the sequence of science AORs. The so-called biased time was defined as the period between the start of an orbit prologue and the end of the subsequent orbit epilogue. Note, that several biased periods were possible during one single cooler hold time and the biased time quoted in Table 1 is the sum of all periods. From OD 128 onwards, the final optimum bias voltages of the PACS detectors were always applied, but on earlier ODs of the Performance Verification and Commissioning Phases bias settings were varied during detector characterization and optimization periods, which can have some impact on the resulting hold time.

Such a dependence was monitored right from the beginning of the mission and after about three quarters of a year there was enough statistics to derive a relation as shown in Fig. 4. The relation

$$t_{\mathrm{hold}}(h) = 72.97\,h - 0.20 \times t_{\mathrm{bias}}(h) \qquad (1)$$

established from all complete cooler periods up to OD 270, irrespective of the start conditions or whether it was a PACS only or parallel mode cooler recycling, was reliably used in the scientific mission scheduling until the end of the mission with a last PACS cooler recycling on OD 1443. The formula was applied for determination of the cooler hold time following both a PACS only and a parallel mode together with the SPIRE cooler recycling.

In (1) t_{hold} can be written as $t_{\mathrm{hold}} = t_{\mathrm{idle}} + t_{\mathrm{bias}}$ with t_{idle} being the fraction of the hold time period with the PACS bolometer detectors not biased, e.g., during spacecraft operational maintenance windows or SPIRE only operations in parallel mode.

In case $t_{\mathrm{idle}} \approx 0$, then (1) can be re-written as

$$t_{\mathrm{bias,max}}(h) = \frac{72.97}{1.2}(h) = 60.8\,h \qquad (2)$$

This meant that a contiguous block of about 2.5 ODs of photometer observations could be scheduled, thus minimizing the cooler recycling frequency. The remaining 0.5 OD was usually filled with PACS spectrometer observations, not requiring ^{3}He cooling, by switching between the two PACS sub-instruments.

Since the cooler hold time relation in (1) was determined for the point in time when the evaporator temperature exceeded an out-of-limit value of 320 mK, a safety time buffer was included when using this relation for mission planning, thus reducing $t_{\mathrm{bias,max}}$ by t_{buffer}. Since the evaporator temperature increased very steeply only

Table 1 PACS cooler statistics. Column 1 gives a running number,distinguishing between PACS only, labeled "A", and parallel, labeled "B", cooler recyclings. Column 2 lists the *Herschel* Operational Day (OD), when the cooler recycling took place and the columns 3 and 4 the start and end times indicated by yyyy-mm-ddThh:mm:ss universal time. Column 5 indicates the start condition of the cooler recycling, whether it started from a warm (w) cooler, with all liquid ^{3}He exhausted, or from a cold (c) cooler, with a remainder of liquid ^{3}He. Column 6 gives the resulting hold time; times flagged by ^{t} are not the fully achievable hold times of this cycle, but are truncated due to an early cold (c) start of a new recycling. These recyclings are not used in Fig. 9. Columns 7 and 8 provide information on the bolometer operations, giving the number of bias periods and the total biased time per cooler cycle. Column 9 flags features of the temperature evolution of the cycle, s: swell ≈24 h after start of recycling, an additional </> indicates significantly shorter/longer than ≈24 h, d: initial dip (see Section 5 for more details). Particular or non-nominal cooler recyclings are flagged with an explanatory footnote

#	OD	start cooler recycling (UT)	end cooler recycling (UT)	start cond.	hold time (h)	# bias periods	biased time (h)	shape T_{EV}
A001	26	2009-06-08T22:40:14	2009-06-09T01:02:36	w	23.8043^t	1	1.1781	s
A002	27	2009-06-10T00:44:57	2009-06-10T03:07:19	c	70.6215	1	6.6511	-
A003	31	2009-06-14T06:32:58	2009-06-14T08:55:20	w	67.7156	1	21.1211	s
A004	38	2009-06-21T07:50:34	2009-06-21T10:12:56	w	34.9333^t	1	2.5333	-
A005	40	2009-06-22T21:03:09	2009-06-22T23:25:31	c	71.2997	2	15.5522	s
A006	46	2009-06-28T17:33:17	2009-06-28T19:55:39	w	71.8910	1	6.4761	s
A007	53	2009-07-06T02:56:06	2009-07-06T05:18:28	w	72.5103	1	2.5250	d
A008	64	2009-07-16T14:47:08	2009-07-16T17:09:30	w	67.0481	2	26.5164	s
A009	67	2009-07-19T14:46:13	2009-07-19T17:08:35	w	67.9420	1	24.6364	s
A010[a]	72	2009-07-24T14:43:23	2009-07-24T17:05:45	w	-	2	38.4600	s
A011	84	2009-08-05T14:52:20	2009-08-05T17:14:42	w	62.9721	3	45.6658	s
A012	92	2009-08-13T20:21:42	2009-08-13T22:44:04	w	68.0481	3	24.2375	s
A013	96	2009-08-17T15:15:43	2009-08-17T17:38:05	w	65.4114	2	40.1767	s
A014	101	2009-08-22T13:27:38	2009-08-22T15:50:00	w	67.0301	1	20.0683	2s
A015	104	2009-08-25T13:35:37	2009-08-25T15:57:59	w	64.8066	2	43.3583	d
A016	107	2009-08-28T13:44:13	2009-08-28T16:06:35	w	45.8214^t	2	41.4394	s<

Table 1 (continued)

#	OD	start cooler recycling (UT)	end cooler recycling (UT)	start cond.	hold time (h)	# bias periods	biased time (h)	shape T_{EV}
A017	109	2009-08-30T13:50:13	2009-08-30T16:12:35	c	42.6895^{t}	2	37.7328	s<
B001	111	2009-09-01T10:19:08	2009-09-01T13:11:40	c	61.5438	2	43.2303	s
A018	118	2009-09-08T23:53:36	2009-09-09T02:15:58	w	58.1821^{t}	2	34.0006	s<
A019	120	2009-09-11T12:21:16	2009-09-11T14:43:38	c	72.7466	1	5.2692	s
A020	124	2009-09-14T23:42:21	2009-09-15T02:04:43	w	60.7143^{t}	2	43.5650	s
A021	127	2009-09-17T14:42:05	2009-09-17T17:04:27	c	62.5602	2	43.7186	s
A022	132	2009-09-23T01:45:58	2009-09-23T04:08:20	w	67.1199	1	18.3050	d
B002	136	2009-09-26T23:12:08	2009-09-27T02:04:40	w	45.1275^{t}	2	37.5689	d
A023	138	2009-09-28T23:06:36	2009-09-29T01:28:58	c	65.3623	2	40.3878	d
A024	146	2009-10-06T22:43:56	2009-10-07T01:06:18	w	45.6248^{t}	1	20.6497	d
A025	148	2009-10-08T22:38:06	2009-10-09T01:00:28	c	45.6031^{t}	2	37.1192	s>
A026	150	2009-10-10T22:32:08	2009-10-11T00:54:30	c	67.0422	2	37.1500	d
A027	156	2009-10-16T22:13:22	2009-10-17T00:35:44	w	64.7625	2	43.7536	d
A028	159	2009-10-19T22:03:37	2009-10-20T00:25:59	w	21.6661^{t}	1	15.0633	d
A029	160	2009-10-20T22:00:21	2009-10-21T00:22:43	c	46.0562^{t}	2	33.8381	s>
B003	162	2009-10-22T21:53:52	2009-10-23T00:46:24	c	45.0942^{t}	4	40.4399	s
A030	164	2009-10-24T21:47:26	2009-10-25T00:09:48	c	67.9650	2	20.6369	2s
A031	171	2009-10-31T21:25:59	2009-10-31T23:48:21	w	63.1170	3	48.5269	s
A032	177	2009-11-06T21:08:55	2009-11-06T23:31:17	w	64.0964	3	42.9447	2s
A033	184	2009-11-13T20:49:39	2009-11-13T23:12:01	w	45.6627^{t}	2	35.5911	d
A034	186	2009-11-15T20:46:04	2009-11-15T23:08:26	c	46.5388^{t}	2	40.0861	d
A035	188	2009-11-17T21:36:12	2009-11-17T23:58:34	c	44.8176^{t}	1	19.9575	s
A036	190	2009-11-19T20:42:49	2009-11-19T23:05:11	c	46.1684^{t}	2	33.3992	2s
B004	192	2009-11-21T20:41:22	2009-11-21T23:33:54	c	65.7532	2	35.2633	s

Table 1 (continued)

#	OD	start cooler recycling (UT)	end cooler recycling (UT)	start cond.	hold time (h)	# bias periods	biased time (h)	shape T_{EV}
A037	197	2009-11-26T20:38:22	2009-11-26T23:00:44	w	46.2087^{t}	2	41.7544	s
B005	199	2009-11-28T20:37:28	2009-11-28T23:30:00	c	67.7568	2	31.2525	d
B006	203	2009-12-02T20:36:11	2009-12-02T23:28:43	w	63.3581	3	45.2086	s<
A038	206	2009-12-05T20:35:46	2009-12-05T22:58:08	w	63.8295	3	45.5047	s
A039	212	2009-12-11T17:42:52	2009-12-11T20:05:14	w	45.8827^{t}	2	42.0986	s
B007	214	2009-12-13T17:22:18	2009-12-13T20:14:50	c	65.2871	2	42.7278	s<
A040	218	2009-12-17T17:24:38	2009-12-17T19:47:00	w	45.7505^{t}	2	39.1311	s
A041	220	2009-12-19T17:26:16	2009-12-19T19:48:38	c	64.1315	3	48.4658	d
A042	223	2009-12-22T17:21:24	2009-12-22T19:43:46	w	62.6322	3	53.5508	d
B008	228	2009-12-27T17:35:37	2009-12-27T20:28:09	w	62.3849	3	48.6158	s
A043	233	2010-01-01T17:49:03	2010-01-01T20:11:25	w	62.7316	3	49.7739	s<
B009	236	2010-01-04T17:49:32	2010-01-04T20:42:04	w	62.6127	3	49.4731	s<
B010	239	2010-01-07T17:55:47	2010-01-07T20:48:19	w	45.2951^{t}	2	31.5111	s
A044	241	2010-01-09T18:00:14	2010-01-09T20:22:36	c	48.1649^{t}	2	39.6519	s<
A045	243	2010-01-11T20:27:54	2010-01-11T22:50:16	c	63.9023	3	48.8775	d
A046	246	2010-01-14T20:35:12	2010-01-14T22:57:34	w	63.1364	3	48.3519	s
A047	251	2010-01-19T18:25:06	2010-01-19T20:47:28	w	62.4450	3	49.9144	d
B011	256	2010-01-24T18:38:36	2010-01-24T21:31:08	w	45.4533^{t}	2	38.9014	s
A048	258	2010-01-26T18:52:33	2010-01-26T21:14:55	c	46.1565^{t}	2	42.9736	d
B012	260	2010-01-28T18:49:38	2010-01-28T21:42:10	c	65.0416	3	39.5114	d
B013	268	2010-02-05T19:11:52	2010-02-05T22:04:24	w	45.8134^{t}	2	34.1367	d
B014	270	2010-02-07T19:17:24	2010-02-07T22:09:56	c	61.8602	3	54.8289	s
B015	274	2010-02-11T20:35:08	2010-02-11T23:27:40	w	65.8847	2	28.8431	s<
A049	284	2010-02-21T18:39:57	2010-02-21T21:02:19	w	61.7253	3	53.8569	s<

Table 1 (continued)

#	OD	start cooler recycling (UT)	end cooler recycling (UT)	start cond.	hold time (h)	# bias periods	biased time (h)	shape T_{EV}
A050	299	2010-03-08T22:40:03	2010-03-09T01:02:25	w	64.6146	2	39.6306	s<
B016	314	2010-03-23T21:14:03	2010-03-24T00:06:35	w	60.7813	3	54.8858	s
A051	320	2010-03-29T23:52:03	2010-03-30T02:14:25	w	62.9215	3	47.4594	d
A052	324	2010-04-02T21:12:41	2010-04-02T23:35:03	w	64.2123	2	41.9975	s
A053	328	2010-04-06T22:01:36	2010-04-07T00:23:58	w	63.6904	3	45.4486	s
A054	343	2010-04-21T23:25:43	2010-04-22T01:48:05	w	62.4411	3	48.4106	d
A055	346	2010-04-24T20:21:49	2010-04-24T22:44:11	w	62.2905	3	51.0150	d
B017	349	2010-04-27T20:38:59	2010-04-27T23:31:31	w	45.6088^{t}	2	37.0225	s
B018	351	2010-04-29T20:32:05	2010-04-29T23:24:37	c	45.3056^{t}	2	37.2692	d
B019	353	2010-05-01T20:08:18	2010-05-01T23:00:50	c	65.1113	3	39.4364	s<
A056	356	2010-05-04T20:15:04	2010-05-04T22:37:26	w	64.1593	2	43.4786	s
A057	360	2010-05-08T19:55:45	2010-05-08T22:18:07	w	64.1401	2	43.0119	d
B020	368	2010-05-16T19:42:22	2010-05-16T22:34:54	w	66.0664	2	27.3881	s
A058	371	2010-05-19T19:37:37	2010-05-19T21:59:59	w	61.8683	3	53.6761	s
B021	374	2010-05-22T19:32:55	2010-05-22T22:25:27	w	64.0344	3	39.7544	s
B022	380	2010-05-28T18:56:03	2010-05-28T21:48:35	w	64.5570	2	38.3961	s
A059	385	2010-06-02T18:40:01	2010-06-02T21:02:23	w	61.5922	3	55.7314	s
B023	392	2010-06-09T14:47:42	2010-06-09T17:40:14	w	47.7938^{t}	2	28.9322	s<
B024	394	2010-06-11T16:52:03	2010-06-11T19:44:35	c	64.7317	3	39.2725	s<
A060	399	2010-06-16T15:59:20	2010-06-16T18:21:42	w	46.1451^{t}	2	43.7475	d
B025	401	2010-06-18T15:54:41	2010-06-18T18:47:13	c	45.1666^{t}	2	36.1786	s
B026	403	2010-06-20T15:22:12	2010-06-20T18:14:44	c	66.4402	3	33.4058	s
A061	413	2010-06-30T15:26:53	2010-06-30T17:49:15	w	61.5300	3	55.8081	s<
B027	416	2010-07-03T15:19:57	2010-07-03T18:12:29	w	62.9263	3	45.7253	s

Table 1 (continued)

#	OD	start cooler recycling (UT)	end cooler recycling (UT)	start cond.	hold time (h)	# bias periods	biased time (h)	shape T_{EV}
B028[b]	420	2010-07-07T15:10:42	2010-07-07T18:03:14	w	-	2	37.7656	s<
B029	434	2010-07-21T14:38:18	2010-07-21T17:30:50	w	45.1509[t]	2	33.6669	s
A062	436	2010-07-23T14:33:39	2010-07-23T16:56:01	c	64.8827	2	44.3497	d
B030	446	2010-08-02T14:31:16	2010-08-02T17:23:48	w	45.6873[t]	2	39.2767	s
B031	448	2010-08-04T14:29:07	2010-08-04T17:21:39	c	45.6707[t]	2	40.9700	s
B032	450	2010-08-06T14:26:58	2010-08-06T17:19:30	c	45.2300[t]	2	35.7411	s
A063	452	2010-08-08T14:28:27	2010-08-08T16:50:49	c	62.1286	3	57.1875	s<
A064	455	2010-08-11T14:21:44	2010-08-11T16:44:06	w	61.5068	3	56.8969	s
B033	458	2010-08-14T14:18:39	2010-08-14T17:11:11	w	61.6184	3	53.4636	d
B034	464	2010-08-20T14:12:37	2010-08-20T17:05:09	w	63.8651	2	42.2944	s
A065	469	2010-08-25T14:07:46	2010-08-25T16:30:08	w	61.5374	3	55.9964	d
A066	472	2010-08-28T14:04:54	2010-08-28T16:27:16	w	62.0021	3	55.0281	s
B035	478	2010-09-03T17:29:21	2010-09-03T20:21:53	w	45.6931[t]	2	40.5706	s
B036	480	2010-09-05T17:27:34	2010-09-05T20:20:06	c	63.5363	2	41.9306	d
A067	483	2010-09-08T17:25:43	2010-09-08T19:48:05	w	62.3834	3	49.4347	s
B037	486	2010-09-11T17:38:46	2010-09-11T20:31:18	w	64.1949	2	40.8369	s
B038	492	2010-09-17T17:34:33	2010-09-17T20:27:05	w	63.7611	2	42.2675	s
B039	497	2010-09-22T17:29:04	2010-09-22T20:01:36	w	45.6872[t]	2	43.4728	s
B040	499	2010-09-24T17:26:55	2010-09-24T20:19:27	c	44.9416[t]	2	38.9772	s
A068	501	2010-09-26T17:11:04	2010-09-26T19:33:26	c	64.9817	2	43.8539	d
A069	511	2010-10-06T17:03:52	2010-10-06T19:26:14	w	61.4005	3	55.6553	s

Table 1 (continued)

#	OD	start cooler recycling (UT)	end cooler recycling (UT)	start cond.	hold time (h)	# bias periods	biased time (h)	shape T_{EV}
B041	514	2010-10-09T17:17:08	2010-10-09T20:09:40	w	70.8895	1	10.5675	s>
B042	521	2010-10-16T16:57:42	2010-10-16T19:50:14	w	63.5320	2	39.9642	s
B043	528	2010-10-23T16:53:24	2010-10-23T19:45:56	w	62.5161	3	45.6708	s
A070	539	2010-11-03T16:12:19	2010-11-03T18:34:41	w	66.0888	2	34.3353	s
A071	545	2010-11-09T16:13:54	2010-11-09T18:36:16	w	62.2343	3	50.3853	s
A072	553	2010-11-17T16:05:23	2010-11-17T18:27:45	w	61.1577	3	57.5881	s<
B044	564	2010-11-28T16:07:55	2010-11-28T19:00:27	w	61.1509	3	54.2536	s<
B045	573	2010-12-07T12:53:27	2010-12-07T15:45:59	w	45.4319^t	2	40.8656	s
B046	575	2010-12-09T12:35:57	2010-12-09T15:28:29	c	45.5978^t	2	41.8775	d
B047	577	2010-12-11T12:29:33	2010-12-11T15:22:05	c	63.2060	3	50.3769	d
A073	581	2010-12-15T12:13:43	2010-12-15T14:36:05	w	46.4597^t	2	44.6547	d
B048	583	2010-12-17T12:27:57	2010-12-17T15:20:29	c	45.7077^t	2	43.1344	d
B049	585	2010-12-19T12:28:04	2010-12-19T15:20:36	c	45.4999^t	2	40.1469	s
B050	587	2010-12-21T12:15:46	2010-12-21T15:08:18	c	62.5957	3	51.6947	d
B051	591	2010-12-25T12:24:44	2010-12-25T15:17:16	w	61.6580	3	53.7583	s
B052	599	2011-01-02T12:02:37	2011-01-02T14:55:09	w	64.5291	2	39.0817	s
B053	603	2011-01-06T10:44:26	2011-01-06T13:36:58	w	45.6712^t	2	39.1711	d
B054	605	2011-01-08T10:41:29	2011-01-08T13:34:01	c	62.9152	3	49.5681	s<
A074	611	2011-01-14T10:18:37	2011-01-14T12:40:59	w	61.7411	3	54.5383	s
A075	614	2011-01-17T10:13:08	2011-01-17T12:35:30	w	61.3934	3	57.7394	s<
B055	619	2011-01-22T10:23:46	2011-01-22T13:16:18	w	61.4251	3	54.0169	s
A076	627	2011-01-30T10:07:57	2011-01-30T12:30:19	w	60.9945	3	58.2303	s
A077	635	2011-02-07T10:13:29	2011-02-07T12:35:51	w	62.0622	3	53.6019	d

Table 1 (continued)

#	OD	start cooler recycling (UT)	end cooler recycling (UT)	start cond.	hold time (h)	# bias periods	biased time (h)	shape T_{EV}
A078	638	2011-02-10T10:15:34	2011-02-10T12:37:56	w	61.6956	3	56.3108	d
B056	647	2011-02-19T10:52:43	2011-02-19T13:45:15	w	61.6607	3	51.5978	d
B057	651	2011-02-23T10:55:22	2011-02-23T13:47:54	w	61.8892	3	52.1847	s
A079	661	2011-03-05T14:19:59	2011-03-05T16:42:21	w	61.2173	3	58.1769	s
B058	668	2011-03-12T23:39:24	2011-03-13T02:31:56	w	61.1985	2	53.7753	s
A080	675	2011-03-19T23:38:21	2011-03-20T02:00:43	w	61.2452	2	56.8564	s
A081	684	2011-03-28T23:49:19	2011-03-29T02:11:41	w	60.8365	2	58.8703	d
B059	695	2011-04-08T21:46:31	2011-04-09T00:39:03	w	61.0576	2	54.6689	s
B060	701	2011-04-15T00:00:09	2011-04-15T02:52:41	w	61.3918	2	53.8089	s
A082	704	2011-04-17T21:22:42	2011-04-17T23:45:04	w	61.2057	2	58.5483	d
B061	712	2011-04-25T23:45:43	2011-04-26T02:38:15	w	45.7131^{t}	2	40.2983	s
B062	714	2011-04-27T23:45:06	2011-04-28T02:37:38	c	62.5411	2	56.5261	d
B063	718	2011-05-01T21:02:38	2011-05-01T23:55:10	w	61.7916	3	53.2950	s
B064	721	2011-05-04T23:48:13	2011-05-05T02:40:45	w	62.2669	3	50.8091	s
B065	724	2011-05-07T23:31:35	2011-05-08T02:24:07	w	61.6951	2	53.5144	s
B066	729	2011-05-12T23:21:24	2011-05-13T02:13:56	w	61.6653	2	53.3042	d
A083	732	2011-05-15T23:02:01	2011-05-16T01:24:23	w	61.3188	2	58.7514	d
B067	737	2011-05-20T23:09:35	2011-05-21T02:02:07	w	61.0989	2	56.1139	s
A084	743	2011-05-26T22:46:20	2011-05-27T01:08:42	w	61.1842	1	58.7111	s
B068	746	2011-05-29T22:56:30	2011-05-30T01:49:02	w	62.6281	3	48.8675	s
B069	749	2011-06-01T22:51:35	2011-06-02T01:44:07	w	62.4941	2	52.5683	s<
A085	757	2011-06-09T18:44:50	2011-06-09T21:07:12	w	61.1722	1	58.5747	s<
B070	762	2011-06-14T18:48:21	2011-06-14T21:40:53	w	60.8709	2	56.1197	s

Table 1 (continued)

#	OD	start cooler recycling (UT)	end cooler recycling (UT)	start cond.	hold time (h)	# bias periods	biased time (h)	shape T_{EV}
A086	769	2011-06-21T16:08:36	2011-06-21T18:30:58	w	60.9551	1	59.0025	s
B071	775	2011-06-27T15:49:27	2011-06-27T18:41:59	w	61.9294	2	51.8719	s
A087	780	2011-07-02T15:14:52	2011-07-02T17:37:14	w	61.1763	1	58.7919	d
A088	787	2011-07-09T14:47:12	2011-07-09T17:09:34	w	61.5607	1	56.6278	d
B072	790	2011-07-12T14:49:47	2011-07-12T17:42:19	w	61.2617	2	56.8269	s
B073	793	2011-07-15T14:42:02	2011-07-15T17:34:34	w	61.1677	2	57.2194	s
A089	797	2011-07-19T14:08:37	2011-07-19T16:30:59	w	61.6677	1	58.2642	s
A090	800	2011-07-22T13:59:03	2011-07-22T16:21:25	w	61.5059	1	58.5600	d
A091	805	2011-07-27T13:19:42	2011-07-27T15:42:04	w	61.2231	1	58.8314	d
B074	808	2011-07-30T13:02:55	2011-07-30T15:55:27	w	61.8302	2	53.5567	s
B075	824	2011-08-15T12:03:04	2011-08-15T14:55:36	w	63.5238	1	43.6217	2s
B076	828	2011-08-19T12:02:32	2011-08-19T14:55:04	w	60.4957	1	58.7331	s
A092	831	2011-08-22T11:19:42	2011-08-22T13:42:04	w	61.0556	1	58.9658	s
A093	842	2011-09-02T14:44:53	2011-09-02T17:07:15	w	60.7562	1	59.1175	d
B077	847	2011-09-07T15:46:55	2011-09-07T18:39:27	w	60.4520	1	59.2228	d
A094	858	2011-09-18T14:53:57	2011-09-18T17:16:19	w	60.9849	1	58.4603	s
A095	871	2011-10-01T15:03:46	2011-10-01T17:26:08	w	60.8517	1	59.0897	s
A096	887	2011-10-17T15:07:36	2011-10-17T17:29:58	w	60.8347	1	59.2342	s
B078	892	2011-10-22T15:19:04	2011-10-22T18:11:36	w	61.3681	2	53.8206	d
A097	898	2011-10-28T15:04:17	2011-10-28T17:26:39	w	61.0836	1	58.1575	s<
B079	904	2011-11-03T15:16:11	2011-11-03T18:08:43	w	60.6198	1	57.3950	s
B080	909	2011-11-08T15:54:23	2011-11-08T18:46:55	w	60.8049	2	56.6389	s
A098	917	2011-11-16T15:01:17	2011-11-16T17:23:39	w	60.9123	1	58.4747	d

Table 1 (continued)

#	OD	start cooler recycling (UT)	end cooler recycling (UT)	start cond.	hold time (h)	# bias periods	biased time (h)	shape T_{EV}
A099	926	2011-11-25T14:56:04	2011-11-25T17:18:26	w	60.9715	1	58.2014	s
B081	930	2011-11-29T15:07:46	2011-11-29T18:00:18	w	61.4486	2	52.3406	d
A100	934	2011-12-03T12:12:53	2011-12-03T14:35:15	w	61.1944	1	56.9378	d
A101	945	2011-12-14T13:02:29	2011-12-14T15:24:51	w	60.8858	1	57.5639	s
A102	955	2011-12-24T11:41:56	2011-12-24T14:04:18	w	60.9793	1	57.1031	s
A103	967	2012-01-05T10:44:52	2012-01-05T13:07:14	w	60.8817	1	57.5353	s
A104	973	2012-01-11T11:41:17	2012-01-11T14:03:39	w	61.0380	1	57.1114	s
A105	981	2012-01-19T10:07:13	2012-01-19T12:29:35	w	61.0445	1	57.4642	s
A106	1000	2012-02-07T10:36:17	2012-02-07T12:58:39	w	60.9549	1	57.3111	s
B082	1005	2012-02-12T10:51:58	2012-02-12T13:44:30	w	60.4919	1	57.3442	s
B083	1026	2012-03-04T13:41:39	2012-03-04T16:34:11	w	60.0322	1	57.3728	s
A107	1034	2012-03-13T01:13:32	2012-03-13T03:35:54	w	61.4201	1	57.7531	s
A108	1037	2012-03-15T23:22:28	2012-03-16T01:44:50	w	61.5980	1	57.6972	d
A109	1040	2012-03-19T00:47:49	2012-03-19T03:10:11	w	61.5788	1	57.8047	s
A110	1043	2012-03-22T00:13:45	2012-03-22T02:36:07	w	62.3290	3[c]	52.5992	d
A111	1049	2012-03-27T21:36:34	2012-03-27T23:58:56	w	61.2187	1	57.3392	s
A112	1057	2012-04-04T21:36:15	2012-04-04T23:58:37	w	60.9807	1	57.3567	s
B084	1063	2012-04-10T21:25:05	2012-04-11T00:17:37	w	62.0468	1	57.0419	s
B085	1074	2012-04-21T21:10:53	2012-04-22T00:03:25	w	60.3257	1	57.4464	s
B086	1081	2012-04-28T20:49:23	2012-04-28T23:41:55	w	60.5841	1	57.4281	s
A113	1095	2012-05-12T19:48:01	2012-05-12T22:10:23	w	60.9746	1	57.6339	d
B087	1101	2012-05-18T19:39:52	2012-05-18T22:32:24	w	60.2460	1	56.3936	s
A114	1108	2012-05-25T19:01:50	2012-05-25T21:24:12	w	61.1698	1	57.5344	s

Table 1 (continued)

#	OD	start cooler recycling (UT)	end cooler recycling (UT)	start cond.	hold time (h)	# bias periods	biased time (h)	shape T_{EV}
A115	1119	2012-06-05T16:44:45	2012-06-05T19:07:07	w	61.0970	1	57.6556	s
A116	1122	2012-06-08T16:43:08	2012-06-08T19:05:30	w	61.3202	1	57.7100	d
A117	1136	2012-06-23T09:10:04	2012-06-23T11:32:26	w	60.8137	1	57.6911	s
A118	1146	2012-07-02T15:57:44	2012-07-02T18:20:06	w	61.2490	1	57.1850	s
A119	1157	2012-07-13T16:30:38	2012-07-13T18:53:00	w	60.9320	1	57.2533	d
A120	1170	2012-07-26T14:40:38	2012-07-26T17:03:00	w	61.0454	1	57.6242	s<
B088	1179	2012-08-04T14:49:35	2012-08-04T17:42:07	w	60.4126	1	57.2525	s<
B089	1182	2012-08-07T15:17:36	2012-08-07T18:10:08	w	60.7152	1	56.8350	s
A121	1193	2012-08-18T14:12:11	2012-08-18T16:34:33	w	61.0950	1	57.0972	s
B090	1196	2012-08-21T13:52:24	2012-08-21T16:44:56	w	60.6987	1	57.2300	d
B091	1200	2012-08-25T16:09:17	2012-08-25T19:01:49	w	60.8055	1	56.9783	s<
B092	1214	2012-09-08T17:21:18	2012-09-08T20:13:50	w	60.1515	1	57.6483	s
B093	1235	2012-09-29T18:36:12	2012-09-29T21:28:44	w	60.3889	1	56.3078	s
A122	1244	2012-10-08T17:31:46	2012-10-08T19:54:08	w	61.0778	1	57.1506	d
B094	1249	2012-10-13T16:54:47	2012-10-13T19:47:19	w	60.3564	1	57.4428	s<
B095	1264	2012-10-28T16:43:06	2012-10-28T19:35:38	w	60.4298	1	56.3814	s<
B096	1270	2012-11-03T16:40:49	2012-11-03T19:33:21	w	60.3439	1	57.5953	d
B097	1273	2012-11-06T16:48:13	2012-11-06T19:40:45	w	60.4971	1	57.1886	s
B098	1279	2012-11-12T21:45:51	2012-11-13T00:38:23	w	60.9443	1	54.7631	s
A123	1285	2012-11-18T21:28:36	2012-11-18T23:50:58	w	60.8648	1	57.5872	d
A124	1293	2012-11-26T21:24:49	2012-11-26T23:47:11	w	61.2999	1	54.7717	s
A125	1308	2012-12-11T14:02:18	2012-12-11T16:24:40	w	60.7747	1	57.6894	s

Table 1 (continued)

#	OD	start cooler recycling (UT)	end cooler recycling (UT)	start cond.	hold time (h)	# bias periods	biased time (h)	shape T_{EV}
A126	1314	2012-12-18T02:36:52	2012-12-18T04:59:14	w	60.6358	1	57.8556	d
A127	1320	2012-12-23T13:34:30	2012-12-23T15:56:52	w	61.0521	1	57.7108	s
A128	1327	2012-12-30T13:26:59	2012-12-30T15:49:21	w	61.0103	1	57.4708	s
A129	1332	2013-01-04T12:29:51	2013-01-04T14:52:13	w	60.8369	1	57.3789	s<
A130	1337	2013-01-09T12:36:54	2013-01-09T14:59:16	w	60.9349	1	57.7964	d
A131	1344	2013-01-16T13:01:53	2013-01-16T15:24:15	w	60.8892	1	57.4214	d
A132	1349	2013-01-21T17:02:54	2013-01-21T19:25:16	w	60.7600	1	57.6244	s
A133	1354	2013-01-26T17:32:26	2013-01-26T19:54:48	w	60.9113	1	57.7697	d
B099	1375	2013-02-16T20:22:35	2013-02-16T23:15:07	w	60.8283	1	55.8261	s
A134	1378	2013-02-19T23:33:12	2013-02-20T01:55:34	w	60.9005	1	57.4461	s
A135	1399	2013-03-12T13:53:09	2013-03-12T16:15:31	w	60.3442	1	57.6919	s<
B100	1402	2013-03-15T13:50:08	2013-03-15T16:42:40	w	60.4554	1	57.6394	s
A136[d]	1418	2013-03-31T13:36:31	2013-03-31T15:58:53	w	65.2737	1	56.3383	d
A137	1426	2013-04-08T14:59:01	2013-04-08T17:21:23	w	60.8467	1	57.7586	d
A138[e]	1440	2013-04-22T14:44:44	2013-04-22T17:07:06	w	57.0020	1	57.7450	s<
A139	1443	2013-04-25T14:42:18	2013-04-25T17:04:40	w	61.0741	1	57.7806	s

[a] PACS switch-off during Onboard Software Upload in DTCP-74, no TM received

[b] TM loss from OD422 to OD424

[c] avoid interference with manual commanding (HIFI)

[d] not nominal: instrument power cycling in the middle of cooler cycle and biased time

[e] not nominal: anomaly in cooler recycling

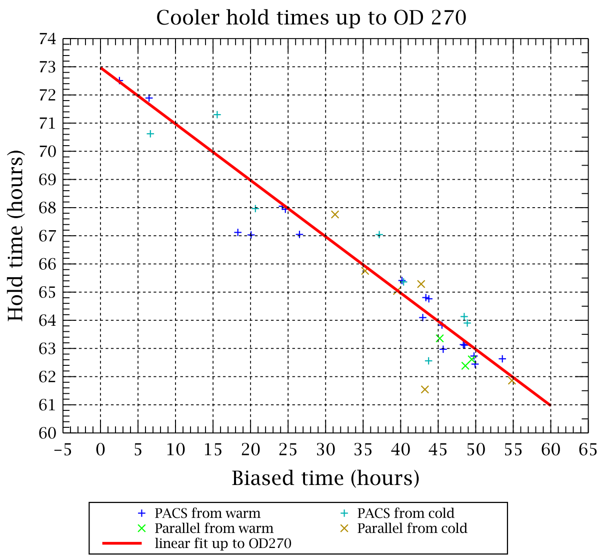

Fig. 4 Relation of the PACS cooler hold time with the operational time of the PACS bolometer detectors for all cooler periods up to OD 270 shown as the *red line* cf. (1). Hold time and biased time are defined in the text at the beginning of Section 4. Different *symbols* and *colors* represent PACS only or parallel mode cooler recyclings and the start conditions from a warm, i.e., exhausted liquid ^{3}He, or a cold, i.e., still available liquid ^{3}He, cooler

at the end of the cooler hold time (see Fig. 5), a buffer of 1.5 h was deemed sufficient initially. However, inspection of photometer calibration observations, scheduled deliberately at the end of the cooler period for cross-calibration with subsequently scheduled PACS spectrometer observations of the same target, showed that there was already an increase in the evaporator temperature (cf. the course of the temperature in Fig. 5 with an increase of up to 5 mK for the two cycles labeled A081 and A093; for the naming convention see beginning of Section 5 and online Table 1) with an impact on the photometric calibration accuracy [1–7]. This effect is described in detail and characterized by appropriate correction functions in [6]. Despite the final calibration and correction of this effect, it was decided to increase t_{buffer} to 3 h, which meant that the evaporator temperature increased by at most 1 mK at the end of the cooler period. This meant a maximum contiguous PACS photometer operation of 57.8 h

5 Mission statistics of cooler recycling

A total number of 239 PACS cooler recyclings was performed during the *Herschel* mission, the first one on OD 26 for PACS commissioning and the last one on OD 1443. 139 cooler recyclings were performed as PACS only (labeled “A” plus a sequence number), 100 recyclings in parallel with the SPIRE cooler recycling (labeled “B” plus a sequence number). It should be noted that the parallel cooler recyclings were not only performed for parallel mode observations of PACS and

SPIRE, but also for separate PACS and SPIRE observations during the subsequent hold time periods. The SPIRE cooler hold time was restricted to about 48 h, the difference between the PACS and SPIRE cooler hold times was usually covered by PACS photometer observations to achieve the highest possible efficiency of each cooler recycling with regard to the foreseen and available photometer observing program.

Online Table 1 gives an overview of all cooler cycles with the achieved hold time and the duration of the PACS detector operations during this hold time. It can be recognized that in the beginning of the mission the detector operational times were relatively short owing to the step-by-step commissioning and performance assessment of the PACS photometer. From about OD 200 onwards, routine observations started achieving usually 40 – 50 h of photometer operations, but this depended also on the instrument allocation per Operational Day due to target visibility and priority

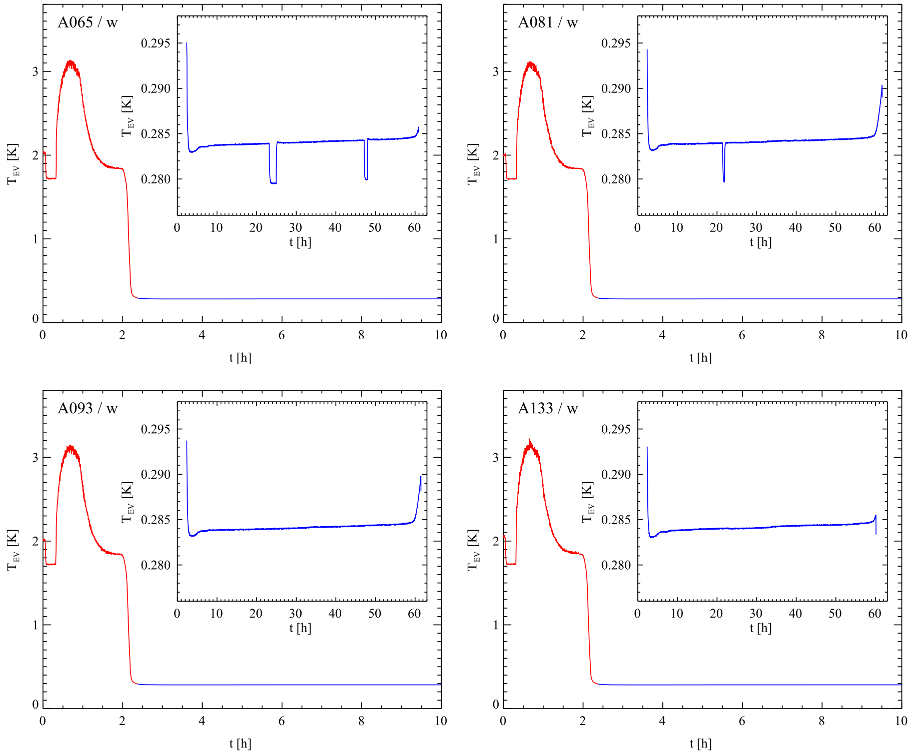

Fig. 5 Individual PACS-only cooler cycles (labeled "A" plus a sequence number, see Table 1) representing the four different operational periods with regard to biasing the detectors. The figure in the main panel shows the course of the evaporator temperature (T_EV) during the first 10 h following the start of the recycling, whereby the *red* part represents the proper recycling process, the *blue* part the beginning of the subsequent operational period. The inserts are a zoomed view with adapted dynamic range of T_EV over the full operational period. *Top left*: Cycle A065 on OD 469 with 3 bias periods, the drops of T_EV to the 280 mK level indicate the unbiased state of the detectors; *top right*: Cycle A081 on OD 684 with 2 bias periods; *bottom left*: Cycle A093 on OD 842 with one maximum contiguous bias period of nearly 59.2 h; *bottom right*: Cycle A133 on OD 1354 with one reduced contiguous bias period of 57.8 h. For the latter one the final steep temperature increase is less than 1 mK

of the observations. In the beginning, the PACS photometer was operated in a safe manner, it was switched into its standby mode by an orbit epilogue AOR, i.e., detectors were de-biased, at the end of each OD and whenever another instrument became prime. This is reflected in the usual 2 – 3 bias periods during this time. This safety aspect could be relaxed along the mission due to the smooth operation of the *Herschel* Space Observatory. From OD 675 onwards, the PACS photometer was switched to standby mode after the first OD of a photometer block, but was then left in biased mode for the subsequent 1.5 ODs. From OD 732 onwards, the PACS photometer was kept in biased mode for the full 2.5 ODs, thus reaching maximum biased times of up to 59.2 h, and later 57.8 h after increasing the buffer time at the end of the hold time (see Section 4). From OD 824 onwards, PACS and SPIRE were operated in most cases simultaneously in prime mode following a parallel cooler recycling without interference in their HK telemetry. This saved time, which had to be spent for the instrument set-up from standby into biased mode, for science observations, but did not mean full permanent observations with PACS during the biased time due to spacecraft operations windows or SPIRE only observations. Nevertheless, this final way of operation yielded the most optimum usage of the PACS and SPIRE photometers for science observations.

Figure 5 shows individual cooler cycles from these different modes of operating the detectors. The periods of unbiased detectors can be clearly recognized by a temperature drop of about 4 mK. After biasing the detectors again, the temperature goes up to the previous level. There is a relatively smooth slight increase of the evaporator temperature during the cycle until the very end when the temperature rises much more steeply. Depending on the safety buffer, this final increase ranges from less than 1 mK for the 3 h buffer to about 5 mK for the 1.5 h buffer.

When inspecting the shape of the cooler evaporator temperature along the cooler cycle, we can distinguish two main types, as illustrated for two subsequent cycles undisturbed by detector bias switching in Fig. 6 (this characteristic difference applies in general also for cycles with detector bias switching).

1) Following the drop to the operational temperature between 282 and 283 mK (if detectors are already biased), the evaporator temperature shows a flat increase. Around 24 h after the start of the cooler recycling, there is a 1 mK high swell in the temperature curve. This usually occurs at around 24 h (not always at exactly the same time), but there are some cases when it already occurs after less than 10 h or only after more than 30 h.
2) Directly after the drop, there is an initial dip followed by the flat temperature rise. A swell does not occur during this cycle.

Most of the cooler cycles, both PACS only and parallel, show the "swell" shape. Column 9 in Table 1 indicates the shape for each cooler cycle. "Swell"-type cycles start at a lower temperature level than "dip"-type cycles and reach the temperature level of the "dip"-type cycle at the time of the "swell". The duration of the "swell" is 2-3 h. The "dip" has a similar duration.

As a summary of the described characteristics of the evaporator temperature evolution, Fig. 7 shows a superposition of all cooler cycles with full hold time and without de-biasing in-between, separately for PACS-only and parallel mode cycles.

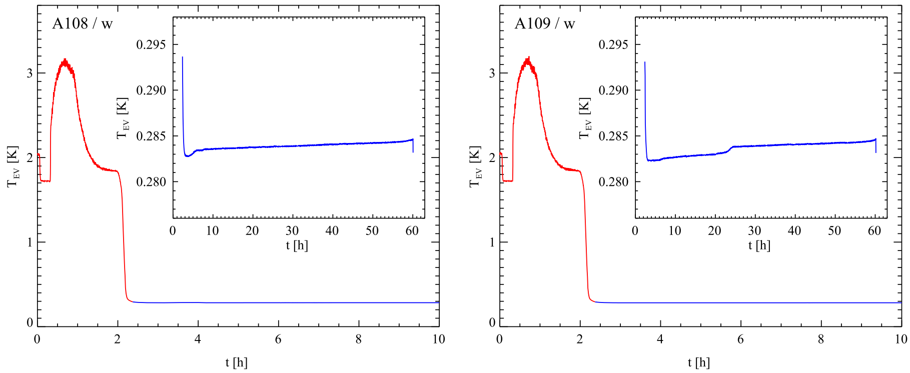

Fig. 6 Examples of the two main types of evaporator temperature evolution during a cooler cycle not disturbed by switching detector biases. *Left*: Initial dip followed by a flat slope. *Right*: "Swell" shoulder with a temperature rise of about 1 mK around 24 h after the start of the recycling. The lay-out and labeling of the panels is the same as in Fig. 5

This reveals fine differences for the two modes of operations. Parallel cycles show an on average slightly higher temperature level, which indicates some small impact by the parallel operations of the SPIRE instrument. This impact is confirmed by the temperature drop after about 48 h, when SPIRE operations terminate. Thanks to the photometric calibration method correcting for time dependent evaporator temperature variation [6], all photometric measurements are put on a homogeneous temperature reference level.

The "dip-type" evaporator temperature curves look similar to the observed on-ground behavior. The "dip" appears therefore to be a consequence of the relative timing of the end of the cooler recycling procedure, when the evaporator temperature still drops, and the bias setting of the detectors as part of the orbit prologue procedure, which leads to the turn of the temperature curve to the level for biased detectors.

We have investigated whether the evaporator temperature "swell" is related to instrument or satellite specific activities. We could not find any strong correlation with instrument switching, long slews, in particular the concluding ones of an OD, or spacecraft operational windows for reaction wheel de-biasing. The physical reason behind the occurrence of the "swells" in the evaporator temperature remains therefore an open issue. We believe it to be a zero gravity effect, possibly related to the liquid arrangement inside the porous material, since it was never observed during tests of the cooler system on ground. Note that for the SPIRE cooler a similar phenomenon has been reported, which has been called the "SPIRE cooler burp".

We also investigated the impact of the detector operations on the shape of the evaporator cooler temperature curve. This is illustrated in Fig. 8. Even with the brightest measurable sources on the detector, the illumination did not cause any noticeable deviations of the evaporator temperature. A noticeable effect could be recognized when the detectors were operated with different bias settings, but this was restricted to a few engineering and calibration observations only.

Figure 9 shows the relation of the cooler hold time versus the biased time for all complete cooler cycles during the mission (192 out of 239, 115 out of 139 PACS

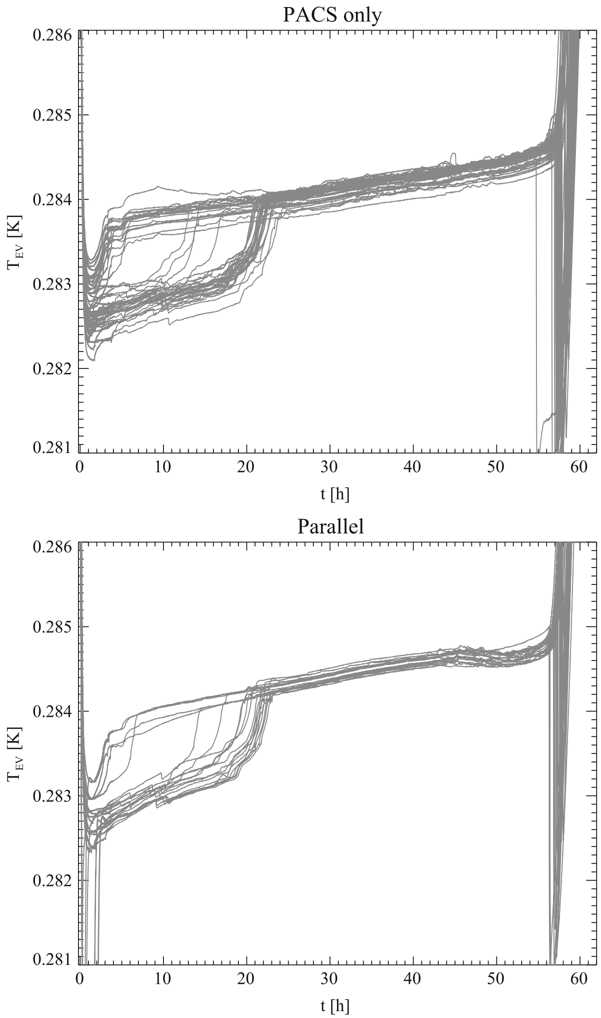

Fig. 7 Superposition of all cooler cycle evaporator temperature curves with full cooler hold time outlining the main characteristics and variation of the two main evaporator temperature evolution families as described in the text. *Top*: PACS-only cycles. *Bottom*: Parallel cycles. The zero point in time is the end of the preceding cooler recycling

only, 77 out of 100 parallel). Cooler periods flagged in Table 1 by a banner "*t*" in the column hold time were not considered, because of their truncation by the start of a new cooler recycling under cold start conditions before the final exhaustion of the liquid ^{3}He.

Plotting all complete hold times of the entire mission shows some fine differences between the different modes and start conditions. The PACS-only recyclings starting from a warm cooler cluster close to the relation established from all complete cooler periods up to OD 270 (cf. Section 4 and Fig. 4), as represented by the red line in

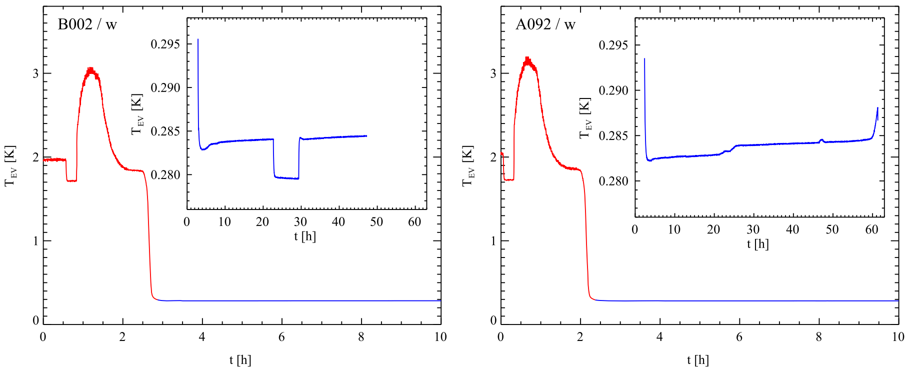

Fig. 8 Examples of cooler cycles with particular detector operations. *Left*: During OD 137 (2nd half of the cycle after the temperature rise terminating the unbiased period, between 38 and 47 h) Mars was illuminating the detector pixels for 9 h. *Right*: During ODs 831 and 832 detectors were operated in a specific engineering mode using a different detector bias setting. These periods are visible as two humps, one on *top* of the evaporator temperature "swell", the other at around 47 h. The lay-out of the panels is the same as in Fig. 5. Labels "A" and "B" with a sequence number represent a PACS-only or a parallel mode cycle, respectively

Fig. 9 with a dispersion of $\approx \pm 0.5$ h. The parallel cooler recyclings starting from a warm cooler are slightly shifted to an about 1 h shorter cooler hold time with a similar dispersion. This one hour less efficiency was well covered by the buffer time applied

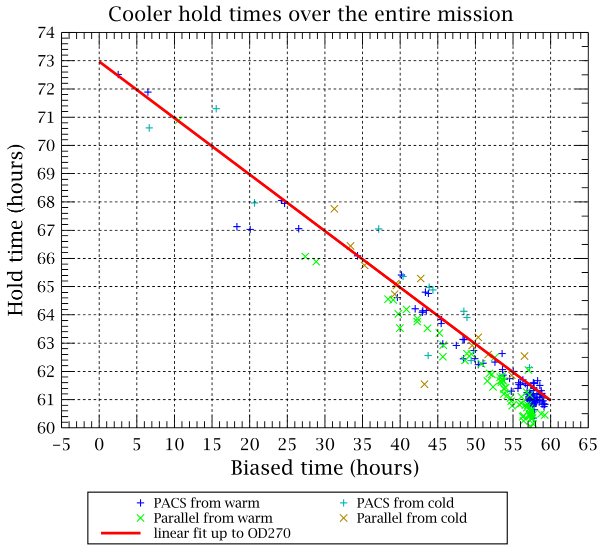

Fig. 9 Statistics of the cooler hold time versus bolometer biased time over the entire *Herschel* mission. Hold time and biased time are defined in the text at the beginning of Section 4. Different symbols and colors represent PACS only or parallel mode cooler recyclings and the start conditions from a warm, i.e., exhausted liquid ^{3}He, or a cold, i.e., still available liquid ^{3}He, cooler. The operational guideline established from the relation of all cooler periods up to OD 270 (cf. Fig. 4) is shown as the *red line*

for mission planning aspects as described in Section 4. Statistics for the cooler recyclings starting from a still cold cooler are poorer, but there is some indication that the hold times both for PACS-only and parallel cooler recycling are about 0.5 h longer than for the warm start PACS-only cooler recyclings.

There are a few outliers with hold times shorter by 1.5 to 3 h than comparable cycles which are restricted to one period between OD 101 and OD 132. Note that this period largely coincides with the period when the bias voltage settings of the PACS detectors were still being varied for detector performance optimization (prior to OD 128).

Formal linear fits like the one for the general hold time relation in (1) yield for all cycles:

$$t_{\text{hold}}(h) = 72.747\,h - 0.205 \times t_{\text{bias}}(h) \tag{3}$$

for PACS-only cycles with warm start:

$$t_{\text{hold}}(h) = 72.523\,h - 0.198 \times t_{\text{bias}}(h) \tag{4}$$

for PACS-only cycles with cold start:

$$t_{\text{hold}}(h) = 72.708\,h - 0.187 \times t_{\text{bias}}(h) \tag{5}$$

for parallel cycles with warm start:

$$t_{\text{hold}}(h) = 72.351\,h - 0.204 \times t_{\text{bias}}(h) \tag{6}$$

for parallel cycles with cold start:

$$t_{\text{hold}}(h) = 72.958\,h - 0.200 \times t_{\text{bias}}(h) \tag{7}$$

Investigation of the cause for the dispersion in cooler hold time for the same biased time has to consider the following aspects:

1) Short term variations of the thermal environment in the order of days.
2) Systematic trends along the *Herschel* mission.

This investigation is illustrated in Fig. 10. For a homogeneous comparison of cooler cycles with very different biased times we calculate the zero bias hold time t_{zbh} as

$$t_{\text{zbh}}(h) = t_{\text{hold}}(h) + f \times t_{\text{bias}}(h) \tag{8}$$

with f being the factors in the relations of (4) and (6), respectively. To account for the slightly different average hold times of PACS only and parallel mode recyclings, the difference of the offsets (72.523 h - 72.351 h = 0.172 h) has been added to t_{zbh} of parallel cycles.

Figure 10 features the following characteristics

1) There is quite some dispersion up to about OD 200 including the mentioned outliers.
2) From OD 200 onwards there are periods with quite low dispersion in t_{zbh} interrupted by periods with higher scatter.
3) There appears to be a slight downward trend of t_{zbh} along the mission.

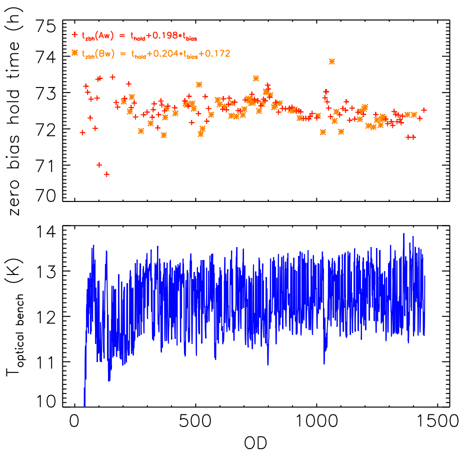

Fig. 10 *Top*: Evolution of the *zero* bias hold time (definition in the text) with mission time represented in Operational Days (ODs) for cooler cycles with a warm (w) start. PACS-only (A) and parallel mode (B) cooler cycles are represented by different symbols. The relations to calculate the *zero* bias hold time are indicated. *Bottom*: Temperature reading of the PACS optical bench sensor which reflects the total thermal input to the PACS focal plane unit

In trying to find correlations with instrument temperature sensing, the PACS instrument optical bench temperature (in the range 10 – 13 K) appears to reflect individual features and overall trends (cf. Fig.10). Note that this is an anti-correlation with low optical bench temperatures corresponding to long hold times and vice versa. It is not always a 1-to-1 anti-correlation in time, but the thermal history also has to be considered. The PACS optical bench temperature is a representation of the total thermal load into the PACS instrument. It depends on activities of all systems inside the cryostat. Switch-off of one of the three instruments, e.g., due to contingency mainly by cosmic ray hits, can cause a significant drop of the thermal load. The thermal load and environment can have an impact both on the recycling process and the evaporation level. We noted some slight systematic variations of the evaporator temperature curves during the recycling, like an increase of the peak temperature and the final 2 K level of the recycling, with proceeding mission.

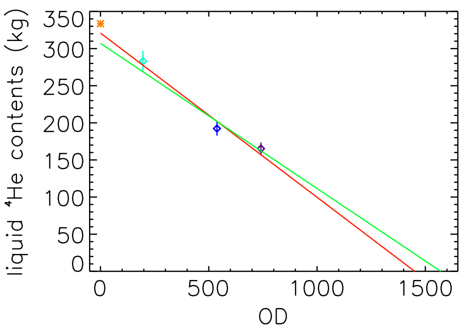

Fig. 11 End of Life (EOL) prediction of the superfluid ^{4}He content in the *Herschel* cryostat on the basis of three dedicated Direct Liquid Content Measurements (DLCM) on ODs 196, 538, and 741. The *solid green* and *red lines* give the best and worst linear fit to the three data points. The point at OD 0 is the mass estimate after the final Helium top-up of the Herschel cryostat prior to launch. Due to the cool-down of the telescope during the first 2 months, the initial Helium consumption is different excluding this point from the fit of the remaining mass in-orbit (source: ESA)

6 Utilization of cooler recyclings to determine the lifetime of ^{4}He in the *Herschel* cryostat

The lifetime of a cryogenic mission is usually determined by the consumption of the initial mass of coolant. In the case of *Herschel* this was the amount of superfluid ^{4}He carried inside the instrument cryostat. For a realistic mission planning trying to execute the essential scientific program a feedback on the remaining lifetime is very helpful. For that reason the *Herschel* cryostat was equipped with special heaters to perform Direct Liquid Content Measurements (DLCM). Three measurements of this type were performed on ODs 196, 538 and 741 by sending a dedicated heat pulse into the superfluid ^{4}He and watching its thermal reaction. This meant however each time the interruption of the scientific observations for several hours to achieve stable thermal conditions and the results did not show a smooth gradual reduction of the ^{4}He mass content, leaving a relatively large uncertainty of about 4 months in lifetime, cf. Fig. 11

The PACS team cryogenic experts developed an alternative method utilizing the regularly executed cooler recyclings of PACS and SPIRE. During the recyclings a well reproducible heat dissipation from the cooler pump into the superfluid ^{4}He L0 bath of the Herschel cryostat took place. Fig. 12 (*top*) shows the corresponding measured temperature rise, which is the higher the less superfluid ^{4}He remains. A smooth and well sampled trend was observed with this method.

With the knowledge of the tank volume, the specific heat capacities of superfluid ^{4}He and He gas in the ullage and the density of both phases, the remaining superfluid ^{4}He mass can be determined. This is plotted in Fig. 12 (*bottom*) and led to a prediction for End of Life in the second half of March 2013. The actual superfluid ^{4}He boil-off happened on 29 April 2013, i.e. the superfluid ^{4}He lifetime turned out to be one month longer than predicted. This is owed to uncertainties in both the adopted physical properties, like e.g. the values of the specific heat capacities, and the start conditions, namely the initial superfluid ^{4}He mass in the tank at launch.

7 The slightly non-nominal cooler recycling on OD 1440

The shape of the relevant cooler temperatures during the recycling as shown in Fig. 3 was highly reproducible during the whole *Herschel* mission until the last recycling on OD 1443, with one exception for the second-to-last recycling on OD 1440, 1 week before the boil-off of the liquid ^{4}He in the large *Herschel* cryostat tank.

Figure 13 shows the temperature evolution which can be compared with the one shown in Fig. 3. It can be noted that TEMP_EV exceeds 3.5 K during the heating of the pump and that the “knee” at around 117 min after thermally disconnecting the evaporator (HSE = 0) and closing the pump heater switch (HSP) is at 2 K and not below. As pointed out in Section 3, the finally achieved TEMP_EV in this step characterizes the efficiency of the recycling. This led to a 3.3 h shorter cooler hold time than anticipated (see Section 4 and Table 1). Due to a safety buffer of 3 h taken into

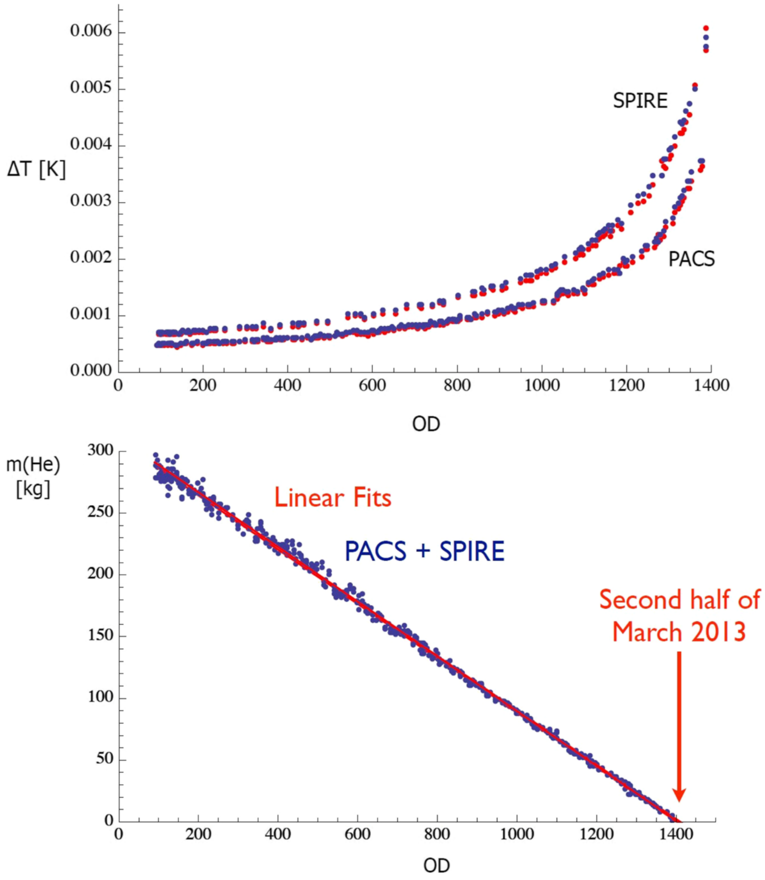

Fig. 12 *Top*: Measured temperature rise of the superfluid ^{4}He L0 bath following the heat dissipation from the PACS and SPIRE cooler recyclings. *Red and blue* dots correspond to the measurement with two different temperature sensors. *Bottom*: End of Life (EOL) prediction of the superfluid ^{4}He content in the *Herschel* cryostat

account by the science mission planning only 0.3 h of PACS photometer observations were lost.[1]

The likely explanation for this behavior is that the remaining liquid ^{4}He film was broken or too thin so that the heat dissipation from the pump was not perfect. This is also reflected in the otherwise not observed bumps in TEMP_TS and TEMP_FPU_ST at about 128 min. This event was the only sign before the final boil-off, that the liquid

[1]The earlier increase of the evaporator temperature triggered an autonomy function and put PACS into safe mode leading to the failure of OBSIDs 1342270750 & 1342270751 planned to observe asteroid (2000) Herschel.

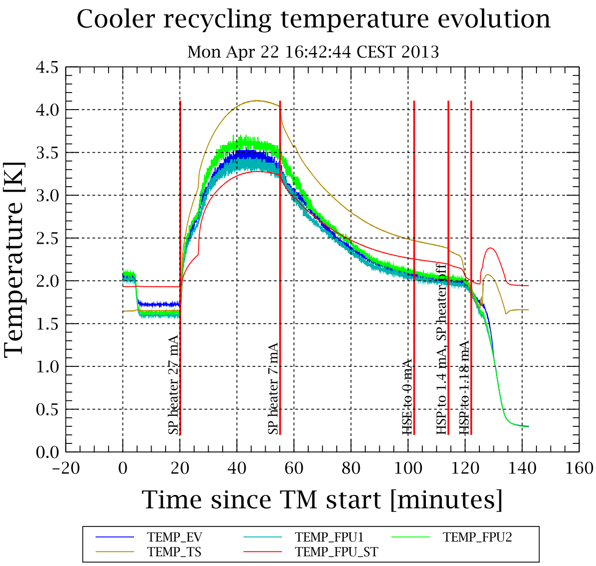

Fig. 13 Evolution of temperatures relevant for the PACS cooler monitored by sensors and provided in the PACS instrument Housekeeping (HK) for the only slightly non-nominal recycling on OD 1440

^{4}He reserve was close to its end. The liquid ^{4}He film recovered again for the next and final PACS cooler recycling on OD 1443.

8 Conclusion

1) The PACS ^{3}He sorption cooler exceeded the required cooler hold time of 46 h by at least 15 h depending on the operational time of the PACS bolometer detectors. The biased time of the detectors is the essential parameter for the resulting hold time. We did not observe any sign of aging effect of the device, despite more than 9 years of operations, almost 4 of them in space.
2) An automatic cooler recycling procedure, assembling the necessary steps with the right timing, worked highly reproducible over the whole mission until the last cooler recycling 4 days before the liquid ^{4}He boil-off in the *Herschel* cryostat. The only slightly non-nominal recycling with a 5% shorter hold time on OD 1440 can be explained by a disturbed thermal interface to the liquid ^{4}He bath 1 week before the boil-off. In total, 139 automatic PACS cooler recyclings and 100 automatic parallel (with SPIRE) cooler recyclings were executed during the Herschel mission.
3) The dependence of the cooler hold time on the detector operational time (biased detectors) was established early in the mission and worked reliably for the science mission planning process over the entire *Herschel* mission.

4) We give a statistics of all PACS cooler recyclings over the full *Herschel* mission. From this fine differences in the performance of the different modes and start conditions can be seen. Parallel cooler recyclings starting with a warm cooler give an about 1 h shorter hold time than PACS-only recyclings. Cooler recyclings starting from a still cold cooler give an about 0.5 h longer hold time than the warm start PACS-only recycling.
5) We characterize the cooler cycles into two main classes: (1) Dip-type cycles starting at a slightly higher level (≈1 mK in evaporator temperature) and, for the majority, (2) swell-type cycles starting at a slightly lower level and usually showing a temperature swell of 1 mK after around 24 h adjusting then to the level of the dip-type cycles. The physical reason for this "swell" is unclear, it appears to be a zero gravity effect. The "dip-type" shapes were also observed during ground tests of the device and seem to be the consequence of relative timing of evaporator temperature evolution and detector bias switching. We also noted a systematically slightly higher evaporator temperature level for parallel cooler cycles during the time interval of SPIRE operations. Illumination conditions of the detectors could be ruled out as negligible.
6) We investigated the cause for the dispersion of cooler hold times of cycles with similar biased time, same mode and start condition, which is in the order of about 1 h. By determining a zero bias hold time, allowing a homogeneous comparison of all cycles, we have seen that the dispersion is caused by trends and different thermal loads into the PACS instrument along the *Herschel* mission. This was concluded from the fact that the PACS optical bench temperature sensor showed a quite good anti-correlation both with regard to long term trends and short term scatter. A few outliers with noticeable shorter hold times can be related to a confined period between OD 101 and OD 132 early in the mission, when larger temperature load variations occurred.
7) The evolution of the cooler evaporator temperature during the individual cooler cycles was studied and the impact of the temperature variation on the bolometer response and hence the photometric accuracy during the biased times could be characterized very well and corrections improving the relative4 calibration accuracy were established as described in [6].
8) We sketch a method of ^{4}He mass content determination evaluating the temperature response of the ^{4}He coolant in the large *Herschel* cryostat to the constant heat deposition of the ^{3}He sorption cooler pump at the end of the recycling process. This gave a much denser and hence robust against individual outliers coverage of the mass content curve for zero cost as an alternative to few dedicated Direct Liquid Content Measurements (DLCM) requiring the interrupt of the scientific operations. The accuracy of the method utilizing the anyhow performed cooler recyclings is solely limited by uncertainties in the adopted physical properties, like e.g. the values of the specific heat capacities, and the start conditions, namely the initial superfluid ^{4}He mass in the tank at launch.

Acknowledgments PACS has been developed by a consortium of institutes led by MPE (Germany) and including UVIE (Austria); KUL Leuven, CSL, IMEC (Belgium); CEA, LAM (France); MPIA (Germany); INAF-IFSI/OAA/OAP/OAT, LENS, SISSA (Italy); IAC (Spain). This development and the operation of the PACS Instrument Control Centre, planning the calibration observations, analyzing and documenting the measurements and supporting the mission planning stray-light protection has been supported by the funding agencies BMVIT (Austria), ESA-PRODEX (Belgium), CEA/CNES (France), DLR (Germany), ASI/INAF (Italy), and CICYT/MCYT (Spain).

Appendix A: Common uplink system (CUS) command script for PACS cooler recycling

```
// Missionphase  :
//
// Purpose       : Perform the cooler recycling
//
// TCL author    : TM
// TCL file      : tm_phot_cooler_recycling.tcl
// CUS author    : DAC
// Script file   : BOLO_cool_recycle.txt
//
// Input arguments
// type    name         description
// N/A
//
// Return values
// Type        Description
// int []      Several duration times
//
// Description   : see PhFPU UM, chapter 4
//
// Dependencies  :
//
// Preconditions :
//
// Comments      : Based on the PhFPU UM Draft 6.0 and
                    abundant e-mail
//                 exchanges with SAp
//
// Version       : 2.0
//
int[] block BOLO_cool_recycle PACS 203 {
}{
    // disable AF 14 (to check for TEMP_EV < 0.3 K)
    Pacs_DPU_SET_FUNCT("EVENT_BOL_T_FPU","DISABLE");
    // disable AF 21 (to check if the absolute value of the
```

```
    HSP current is below 2*10^(-5)A)
Pacs_DPU_SET_FUNCT("EVENT_BOL_I_SP1","DISABLE");
// enable AF 18 (to check if the current of the sorption
    pump heater is below 30mA)
Pacs_DPU_SET_FUNCT("EVENT_BOL_I_SP2","ENABLE");
//
// Obtain and set Block ID
WriteBBID($BBID);
// Define variables to communicate various durations
    to HSPOT.
// NOTE: all time variables in units of number of ramps
         (SPEC) or
//       number of readouts (BOLO). The calling program
          must convert this
//       count into actual duration in true time units
          [seconds].
//       SRC, REF, CAL, OVR stand for time spent on SRC,
          REF (on sky),
//       CAL source, and overheads (wait for something).
           Total
//       duration is given by duree_num. If no error,
          this duration
//       must be equal to the sum of all others
// NOTE: here all durations are given in [sec]
int duree_num = 0;
int duree_SRC = 0;
int duree_REF = 0;
int duree_CAL = 0;
int duree_OVR = 0;
// Set HK to PHOT
Pacs_DPU_SET_HK_LIST("PHOT","BOTH Array");
// content of "Preparation_au_recyclage.txt"
// Set SP heater current to  to 0.00000000 amperes (0)
// # P 07 01 0000
int operand = 0x7010000;
Pacs_DMC_SEND_COMMAND_BOLC(operand);
int t_wait = 1;
delay(t_wait);
duree_num = t_wait;
duree_OVR = t_wait;
// Set HSP heater current to  to 0.00000000 amperes (0)
// # P 07 02 0000
operand = 0x7020000;
Pacs_DMC_SEND_COMMAND_BOLC(operand);
t_wait = 1;
```

```
delay(t_wait);
duree_num = duree_num + t_wait;
duree_OVR = duree_OVR + t_wait;
// Set HSE heater current to  to 0.00140000 amperes (3572)
// # P 07 03 0DF4
// Attendre 300000 ms
// # S 01 0493E0
operand = 0x7030df4;
Pacs_DMC_SEND_COMMAND_BOLC(operand);
t_wait = 300;
delay(t_wait);
duree_num = duree_num + t_wait;
duree_OVR = duree_OVR + t_wait;
// Set HSE heater current to  to 0.00118000 amperes (3011)
// # P 07 03 0BC3
// Attendre 900000 ms
// # S 01 0DBBA0
operand = 0x7030bc3;
Pacs_DMC_SEND_COMMAND_BOLC(operand);
t_wait = 900;
delay(t_wait);
duree_num = duree_num + t_wait;
duree_OVR = duree_OVR + t_wait;
//*********************************************************
//**                                                     **
//**     Automatic Cooling reclycling                    **
//**     ("Recyclage_Auto_Time.txt")                     **
//**                                                     **
//*********************************************************
//
// - 23/01/06 Procedure of reclycling in Saclay cryostat
      with Phfpu MV
// - note : this is timing version without temperature test
//
//          Initialisation of BOLC
//
// Set temp probe on/off FF hexa
// # P 07 00 00 FF
//
//          Initialisation of LTU
//
// Inhiber enregistrement TM
// # S 08
// Valider enregistrement TM
// # S 09
```

```
//
// Initial conditions
// TEMP_SP < 10K
// TEMP_EV < 2K
//
// Set SP heater current to  to 0.02730000 amperes (2231)
// # P 07 01 08B7
//
// Attendre 2100000 ms
// # S 01 200B20
operand = 0x70108b7;
Pacs_DMC_SEND_COMMAND_BOLC(operand);
t_wait = 2100;
delay(t_wait);
duree_num = duree_num + t_wait;
duree_OVR = duree_OVR + t_wait;
//
// Set SP heater current to  to 0.00700000 amperes (580)
// # P 07 01 0244
//
// Attendre 2820000 ms
// # S 01 2B07A0
operand = 0x7010244;
Pacs_DMC_SEND_COMMAND_BOLC(operand);
t_wait = 2820;
delay(t_wait);
duree_num = duree_num + t_wait;
duree_OVR = duree_OVR + t_wait;
//
// Set HSE heater current to  to 0.00000000 amperes (0)
// # P 07 03 0000
//
// Attendre 720000 ms
// # S 01 0AFC80
operand = 0x7030000;
Pacs_DMC_SEND_COMMAND_BOLC(operand);
t_wait = 720;
delay(t_wait);
duree_num = duree_num + t_wait;
duree_OVR = duree_OVR + t_wait;
//
// Set SP heater current to  to 0.00000000 amperes (0)
// # P 07 01 0000
operand = 0x7010000;
Pacs_DMC_SEND_COMMAND_BOLC(operand);
```

```
t_wait = 1;
delay(t_wait);
duree_num = duree_num + t_wait;
duree_OVR = duree_OVR + t_wait;
//
// Set HSP heater current to  to 0.00140000 amperes (3569)
// # P 07 02 0DF1
//
// Attendre 480000 ms
// # S 01 075300
operand = 0x7020df1;
Pacs_DMC_SEND_COMMAND_BOLC(operand);
t_wait = 480;
delay(t_wait);
duree_num = duree_num + t_wait;
duree_OVR = duree_OVR + t_wait;
//
// Set HSP heater current to  to 0.00118000 amperes (3010)
// # P 07 02 0BC2
operand = 0x7020bc2;
Pacs_DMC_SEND_COMMAND_BOLC(operand);
t_wait = 1;
delay(t_wait);
duree_num = duree_num + t_wait;
duree_OVR = duree_OVR + t_wait;
//
// ***********************
// **                   **
// ** end recycling     **
// **                   **
// ***********************
//  Last message
debug_print("Recycling completed, in about 20 min,
 TEMP_EV < 0.3 K");
t_wait = 1200;
duree_num = duree_num + t_wait;
duree_OVR = duree_OVR + t_wait;
delay(t_wait);
//
// AF settings
//
// disable AF 18 (to check if the current of the sorption
    pump heater is below 30mA)
Pacs_DPU_SET_FUNCT("EVENT_BOL_I_SP2","DISABLE");
// enable AF 21 (to check if the absolute value of the HSP
```

```
        current is below 2*10^(-5)A)
    Pacs_DPU_SET_FUNCT("EVENT_BOL_I_SP1","ENABLE");
    //
    // Set HK to NO PRIME (to have the clean SAFE settings again)
    Pacs_DPU_SET_HK_LIST("NO_PRIME","BOTH Array");
    // Return the array of times
    int[] time_array = [duree_num,duree_SRC,duree_REF,
     duree_CAL,duree_OVR];

    return time_array;
}
```

References

1. Balog, Z., et al.: The herschel-PACS photometer calibration. Point-source flux calibration for scan maps. Exp. Astron. (2013). doi:10.1007/s10686-013-9352-3
2. Billot, N., et al.: CEA bolometer arrays: the first year in space. Proc. SPIE. **7741**, 11 (2010). article id. 774102
3. Duband, L., et al.: A thermal switch for use at liquid helium temperature in space-borne cryogenics systems. In: Proceedings of the 8th International Cryocooler Conference, pp. 731–741. Plenum Press, NY (1995)
4. Duband, L., et al.: Herschel flight models sorption coolers. Cryogenics. **48**, 95 (2008)
5. Griffin, M.J., et al.: The herschel-SPIRE instrument and its in-flight performance. A & A **518**, L3 (2010)
6. Moór, A., et al.: PACS photometer calibration block analysis. Exp. Astron. this volume (2013)
7. Nielbock, M., et al.: The herschel PACS photometer calibration. A time dependent flux calibration for the PACS chopped point-source photometry AOT mode. Exp. Astron. (2013). doi:10.1007/s10686-013-9348-z
8. Pilbratt, G.L., et al.: Herschel space observatory. A & A **518**, L1 (2010)
9. Poglitsch, A., et al.: The photodetector array camera and spectrometer (PACS) on the herschel space observatory. A & A **518**, L2 (2010)