LFI Radiometric Chain Assembly (RCA) data handling “Rachel”

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ABSTRACT

Planck’s Low Frequency Instrument is an array of 22 pseudo-correlation radiometers at 30, 44, and 70 GHz. Before integrating the overall array assembly, a first set of tests has been performed for each radiometer chain assembly (RCA), consisting of two radiometers. In this paper, we describe Rachel, a software application which has been purposely developed and used during the RCA test campaign to carry out both near-realtime on-line data analysis and data storage (in FITS format) of the raw output from the radiometric chains.

Key words. Software Engineering; Data Handling; Microwave Antennas; Spectral responses

1. Introduction

Planck is an ESA mission designed to map the angular distribution of the cosmic microwave background (CMB). It will scan the sky in 9 frequency channels, from 30 GHz to 857 GHz, with two instruments; the Low Frequency Instrument (LFI, 30-70 GHz) and the High Frequency Instrument (HFI, 100-857 GHz). Planck/LFI is an array of 22 pseudo-correlation differential radiometers, cryogenically cooled at 20K, coupled to the telescope by 11 dual profiled corrugated feed horns (Mandolesi et al. 2009; Tauber et al. 2009). Accordingly, Planck/LFI can be described as being composed of 11 independent units, or Radiometer Chain Assemblies (RCAs), each consisting of 2 pseudo-correlation radiometers and their 4 detectors, that is, 2 channels for each radiometer, switching between a sky-load and a reference-load to perform differential measurements (Bersanelli et al. 2009). The functional and calibration test of single RCAs has been one of the first steps of Planck/LFI overall calibration campaign (see Bersanelli et al. 2005; Mennella et al. 2006). The main purpose of the test was to verify and measure the individual performance of the 11 RCAs. Two dedicated cryofacilities have been used during the test campaign: the 30 and 44 GHz radiometer chains were tested at Alcatel – Alenia Space in Italy, while the 70 GHz channels were calibrated at Elektrobit in Finland.

From the point of view of on-line data analysis and storage, testing one radiometric chain implies both the acquisition and the recording, in form of FITS tables, of several flows of information: output from the four switching channels (i.e. two sky/reference pairs, one for each receiver), temperature probes, facility’s setup and bias-related parameters, and user-provided log-entries. Moreover, a real-time graphic and numerical analysis is required, in order to check that the functional and environmental conditions of the test-in-progress meet the test requirements.

To perform these operations at the required rate (each channel being sampled at 14bits and 8192Hz, the incoming data rate was around 0.5Mb/s), dedicated software, Rachel (Radiometric Chains Evaluator), has been designed and developed in an open source environment (Linux), using only open source libraries and tools: GCC (GNU CC Project 2009), Qt3 ( Trolltech Website 2003), CFITSIO (HEASARC Software Archive 2008), FFTW (Frigo & Johnson 2005; FFTW Website 2009), and MySQL (MySQL Documentation 2009). Rachel is open source as well, and its source code is available to the community, upon request (zacchei@oats.inaf.it), on the CVS server of the Planck/LFI Data Processing Center in Trieste.

Because of its high level of customizability and of its user-friendly interfaces, besides this Planck/LFI-specific application, Rachel could also be employed in many other contexts where data analysis and storage of one or more 180° phase-shifted signal/reference pairs is required.

In this paper, the architecture and performance of Rachel are illustrated. Section 2 describes the test configuration. Section 3 briefly reports the software performance and architecture. Section 4 illustrates the main interfaces and analysis tools provided by Rachel. The WEB-based remote-monitoring tool is depicted in Sect. 5, while Sect. 6 describes the structure of the FITS tables where test data are stored.
2. RCA data acquisition configuration

The units involved in each RCA test (Fig. 1) were:

1. inside the cryofacility, the RCA itself, consisting of the sky feed horn and a couple of small pyramidal horns, all feeding the 20K cooled Front End Module (FEM), and then a set of waveguides propagating signal to the 300K Back End Modules (BEM). The feed horn and the two small antennas look, respectively, at an external wide band blackbody (or sky simulator) and at two reference loads, whose 4K temperature is provided by a dedicated helium cryocooler (Terenzi et al. 2007);

2. outside the cryofacility, the Data Acquisition Electronics (DAE) and a PC running a LabView application for raw data acquisition and board control;

3. the Rachel workstation.

In terms of information flow, transmission from FEM to BEM is via waveguide; from BEM to the DAE, using analog signals over wire; from DAE to the LabView PC, using digital signals; finally, from the LabView PC to the Rachel workstation, through TCP/IP network sockets in a client-server configuration, with Rachel acting as a server and LabView as a client.

Besides scientific data (i.e. the output from the four RCA detectors), network sockets are used also to acquire the output from temperature or current probes, the DAE configuration, and log-entries from the LabView PC.

3. Rachel's main tasks and performance

Since LFI science and housekeeping data are sampled at fixed rate, the expected maximum average incoming data rate can be easily predicted: 533568 b/s (see Table 1; configuration and log-entries packets contribution can be safely assumed as insignificant, since they are sporadically generated only after manual operations). In order to have a margin of safety, Rachel has been designed to keep up with an incoming data rate up to 1 Mb/s without losing any packets. This requirement has been tested using a simple RCA simulator, “RcaClient”, expressly developed to generate RCA-like network packets at a user-configurable data rate. Even the slowest computer we used for the test, a P3@800 MHz notebook, has been found to be able to meet the requirement. On a P4@2.8 GHz, that is a machine comparable to those actually used during the RCA test campaign, Rachel process average CPU load with data recording enabled and 1 Mb/s incoming rate, measured with the Linux “top” utility, is between 15% and 20%.

The minimal set of tasks that Rachel is required to perform in real-time, while keeping up with the incoming network packets, are:

1. Listening and acquiring data on a loss-less protocol (TCP/IP) from four network sockets, as illustrated in Table 1.
2. Recording incoming data as FITS tables on the local hard disk (see Sect. 6).
3. Providing graphical and numerical real-time analysis and quick-looks of the incoming data.

The most CPU-consuming operation, thus the most potentially critical point of the whole application in terms of performance, is the production in near-real-time of two Hi-Freq FFT (one for sky samples, the other for the reference samples; see Sect. 4.5) and three Lo-Freq FFT (sky samples, reference samples, and their difference; see Sect. 4.6) per second for each channel: thus, 20 FFT/s, each one over a window of 4096 points. Quantitatively, using a sample of 110 seconds on a P4@2.8 GHz acquiring data at nominal rate (533568 b/s), we have profiled an average time of 1.0 ± 0.1 ms for the Hi-Freq FFTs and 1.0 ± 0.2 ms for the Lo-Freq FFTs: that is, 20 ms per second of acquisition. During the same test, CPU time for the statistical estimators (see Sect. 4.7) has been found to be 0.7 ms per second, while the correlation calculations (see Sect. 4.8) required 8 ms per second.

4. The real-time graphic and numerical analysis interfaces

As regards data analysis, Rachel’s main task is to provide a quick-look of the incoming signal and of its noise properties. In this section, we shall illustrate the statistical tools and graphic interfaces which have been implemented in Rachel to achieve this purpose.

4.1. Oscilloscope-like strip chart

The oscilloscope window, located in the upper-left corner of Rachel (Fig. 2), shows a real-time plotting of channel values (Y-axis) over time (X-axis). Each channel is represented by a user-selectable color. In order to disentangle overlapping channels, they can be individually obscured. Upper and lower limits of the visible window are reported on the right, and can be increased or decreased by the
Due to the high sampling rate (8192 Hz) and to the phase-shifting strategy, a raw representation of the incoming data flow would hardly be decipherable. To improve readability, channels are first split into their sky/reference components, then graphically binned over a user-selectable number of samples, \( N_{\text{tmp}} \), varying in the range from 4 to 512. Thus, the X–axis extension in seconds, \( \Delta X \), whose value is displayed in the lower left corner, is dependent on \( N_{\text{tmp}} \) and the sampling rate \( r_{\text{tmp}} \) (in Hz):

\[
\Delta X = \frac{1024N_{\text{tmp}}}{r_{\text{tmp}}}.
\]

Finally, whenever the cursor is located over the chart, the value of the pixel it is pointing at will be shown next to the Cursor label, in volt or in Kelvin according to the unit option.

### 4.2. Multi-channel analyzer distribution chart

The multi-channel sub-window, located on the upper-right corner of Rachel (Fig. 2), offers a graphic representation of the data frequency distribution. In the case of a noise-dominated signal, it thus allows a qualitative estimate about its Gaussianity (for a quantitative approach based on skewness and kurtosis, see Sect. 4.7). The visible window is zoomable and scrollable along both the X–axis (distribution classes, or bins) and the Y axis (frequency density). The size of the bins can be increased or decreased clicking on the «plus» and «minus» buttons next to the horizontal scrollbar. As regards bin size, the lower limit corresponds to the LSB of the ADCs (one bin per pixel), while the upper limit is set to make the maximum ADC range coincide with the window width.

In order to keep the distribution curve in range, the Y-axis scale is automatically increased whenever the frequency density of the mode reaches the upper limit. For the same purpose, an auto-zooming algorithm has been implemented which adjusts automatically the vertical scale whenever the size of the bins is decreased. Obviously, both these mechanisms can be overridden by users clicking the «plus» and «minus» buttons next to the vertical scrollbar: this can be very useful when the four channels have show different behaviors, or to deal with spikes in the frequency density.

Finally, as in the oscilloscope window, each channel is represented by a user-selectable color, and a Cursor label will show, numerically, the frequency density of the bin pointed by the cursor. Hence, it is possible to have, at a glance, a quick estimate of the statistical dispersion of the samples.

### 4.3. Strip chart of the temperature probes

The strip chart of the temperature probes allows the user to keep track of any variation in the environmental condition during the latest five minutes of acquisition. The chart itself is functionally similar to the oscilloscope tool (see Sect. 4.1), and the latest value of each probe is numerically reported as well. Actually, the choice of an unchangeable five minutes interval has been rather arbitrary: initially, it had been dictated merely by the width of the window (300 pixels) and the temperature probes sampling rate (1 Hz), thus resulting in 300 seconds of non-binned data. Anyway, since during the first tests an interval of five minutes has proved satisfactory for checking temperature trend and stability, we have never implemented a feature to make it user changeable.

### 4.4. Overall statistics

The overall statistics sub-window, located on the lower-left corner of Rachel (Fig. 2), displays numerical information about the scientific channels.

Each channel is split into its sky and reference components, and the difference between them is reported as well. The VALUE columns show the latest value, while the AVERAGE and the STDEV columns show the average and the biased standard deviation of non-binned samples over all the data acquired since Reset statistics was last invoked. The LCD-like figures in the upper-left corner of the statistics sub-window is the sample counter, and it is zeroed every time that statistics are reset. Statistics are directly performed on the incoming data flow, and are refreshed every 0.5s.

The check boxes on the left of the channel names affect the behavior of the oscilloscope: they allow the user to enable or dis-

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### Table 1. Network sockets

| Port   | Content                                                                 | Packet structure                                                                 | Packet and Bit Rate |
|--------|-------------------------------------------------------------------------|----------------------------------------------------------------------------------|---------------------|
| 18000  | Scientific data from the 4 channels.                                     | Synchronous network packets, each containing one packet counter (4 bytes), the time code (4 bytes), and 64×4 scientific values (unsigned 16bits words), for a total packet size of 520 bytes. | 128 pkt/s 532480 b/s |
| 18001  | Temperature and current data from the probes.                           | Synchronous network packets, each containing one packet counter (4 bytes), the time code (4 bytes), 28 temperatures (4 bytes float), and 4 currents (4 bytes float), for a total packet size of 136 bytes. | 1 pkt/s 1088 b/s    |
| 18002  | DAE configuration parameters.                                           | Asynchronous network packets, each containing one packet counter (4 bytes), the time code (4 bytes), 6 environmental data (4 bytes float), and 32 bias data (1 byte), for a total packet size of 64 bytes. | N/A N/A             |
| 18003  | Log-entries.                                                            | Asynchronous network packets, each containing one packet counter (4 bytes), the time code (4 bytes), and one entry line (248 bytes), for a total packet size of 256 bytes. | N/A N/A             |

Minimum average incoming data rate 533568 b/s
able the plotting of the selected channel component and of its dispersion inside the graphical bin.

4.5. High frequency FFT

Each high frequency FFT dialog box (Fig. 3, on the left) displays the power spectrum, for components above 1Hz, of the sky and reference values of one scientific channel. Since one RCA has four channels, as explained in the Introduction, Rachel provides four independent Hi-Freq FFT windows. Users can toggle the visibility of each of these windows through the FFT menu.

Fig. 3. High Freq FFT (left) and Low Freq FFT (right) dialog boxes.

The FFTs are performed over the latest 8192 samples/channel. Sky and reference values being treated separately, each FFT takes as input 4096 homogeneous samples, that is one second of data, and produces a vector of components which ranges from 1 to 2047 Hz ($\frac{1}{2}f_{Nyquist} - 1$).

Since in the RCA tests frequencies above 1Hz are expected to show a flat spectrum, these dialogs can be useful to detect unexpected components—notably, the 50 Hz interference from power supplies and microphonic noise. Users can choose whether to represent frequencies over a logarithmic or a linear axis, while amplitudes can be shown both in Volts or in dBV:

$$A_V = \frac{1}{N} \sqrt{R_{FFT}^2 + I_{FFT}^2}$$ (2)

$$A_{dBV} = 20 \log (A_V)$$ (3)

where $R_{FFT}$ and $I_{FFT}$ are, respectively, the real and the imaginary part of the FFT output, and $N$ is the number of components. On the left of each graph there is a zooming bar which allows the user to increase or decrease the Y-axis range. Whenever the cursor is located over one of the two charts, the frequency and the amplitude of the pixel it is pointing at will be shown next to the X-cursor and Y-cursor labels, thus allowing the user to single out frequency classes which show anomalous peaks.

4.6. Low frequency FFT

Low frequency FFT dialog boxes (Fig. 3, on the right) are similar to High Frequency FFTs, the main difference being that they take into account the 0.2-500 mHz components. Furthermore, besides the sky and reference windows, they provide a third FFT window for the difference between sky and reference. Their main purpose is to provide a rough outline of the $1/f$ noise contribution, the $1/f$ knee frequency expected for the LFI detectors being below 50 mHz (Maino et al. 1999).

4.7. Statistical estimators

The statistical estimator dialog boxes (Fig. 4) provide, for the latest five minutes of acquisition, real-time statistical estimators (refresh frequency: 1Hz) for each channel’s sky and reference pairs: average, standard deviation, skewness, and kurtosis. Skewness and kurtosis, giving a numerical estimate of the degree of the asymmetry and of the peakedness of the distribution, allow the user to quantify the (non-)gaussianity of the incoming signals. The graph of the standard deviation trend can be useful to detect noise instabilities and fluctuations. Five minutes is

Fig. 4. Statistical estimators dialog box.
a convenient interval to graphically compare noise fluctuations with the values displayed in the temperature strip charts (Sect. 4.3).

4.8. Correlations discoverer

The correlations discoverer dialog boxes (Fig. 5) calculate and represent in real-time (refresh frequency: 1Hz) the matrix of correlation coefficients between incoming scientific data and temperature probes. They also calculate the linear regression, and display a correlation graph for the selected channel/probe pair. This tool is extremely useful to detect at a glance both unexpected correlations (due, for instance, to unforeseen thermal couplings) and the absence of predictable correlations.

5. SQL-based WEB interface for remote monitoring

Because of the long duration of many RCA tests and the consequent need to monitor the behavior of the chains also from remote facilities, a SQL-based WEB interface has been added to Rachel (Fig. 6).

An interface, known as “Rachel-WEB”, displays a numerical quick-look of the on-going test and its main parameters (science data, currents, and temperatures). The refresh frequency of Rachel-WEB data is 1Hz, thus it acts as a simplified near-realtime quick-look.

In order to minimize the impact of this interface on Rachel’s performance, averaged data are stored into a MySQL database through low priority buffered queries, which do not introduce wait states. The same database has also been used to keep track of the trend of each test, thus providing a permanent, shared and searchable catalogue to retrieve FITS files from one or more sessions of test.

6. FITS files production

In order to make test results available to the off-line analysis tools and DB (Zacchei & Franceschi 2004), data from RCAs calibration tests are stored in FITS format. As specified by LFI DPC data management requirements, four separate files are generated for each test: each file contains a collapsed primary array and one Header and Data Unit (Zacchei & Franceschi 2005). The Data Unit contains data from one network socket only, while the Header contains a set of card images (or Keyword Records, as they have been renamed in the latest revision of the FITS standard) which is shared by all the files. The module which provides Rachel on-line FITS storage functionality is called fitswriter. Basically, fitswriter is a C++ wrapper built around the CFITSIO library (see HEASARC Software Archive 2008). Its goal is to maintain the maximum control over the implementation details and to meet the FITS format specifications given above. Moreover, through a clear-cut separation between the project-dependent classes and the generic ones, it guarantees a high reusability of the code.

A graphical sample of the fitswriter classes, expressed in Unified Modeling Language, is given in Fig. 7.

7. Conclusions

All the data acquired during the RCAs tests carried out at Alcatel Alenia Space (Italy) during 2004 and at Elektrobit (Finland) in the summer of 2005 have been successfully processed and viewed using Rachel. Many issues in the test data have been detected and efficiently managed thanks to its advanced quick-look interface.
About 220 gigabytes of FITS files have been produced and made available for the subsequent offline data analysis phase (see Tomasi et al. 2009).

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