QUIJOTE Experiment.
Status of Telescopes and Instrumentation.

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ABSTRACT

The QUIJOTE Experiment (Q-U-I JOint TEnerife) is a combined operation of two telescopes and three instruments working in the microwave band to measure the polarization of the Cosmic Microwave Background (CMB) from the northern hemisphere, at medium and large angular scales. The experiment is located at the Teide Observatory in Tenerife, one of the seven Canary Islands (Spain).

The project is a consortium maintained by several institutions: the Instituto de Astrofísica de Canarias (IAC), the Instituto de Física de Cantabria (IFCA), the Communications Engineering Department (DICOM) at Universidad de Cantabria, and the Universities of Manchester and Cambridge. The consortium is led by the IAC.

Keywords: microwaves, polarization, CMB, B-modes, telescopes, instrumentation, cryogenics, Temperature control.

1. INTRODUCCION

The overall scientific target is the characterization of the polarization signal of the primordial CMB in the frequency range 10–47 GHz, as well as other galactic and extra-galactic sources, specifically the synchrotron and the anomalous microwave emission that are detectable at low frequencies and not sufficiently understood as sources of polarized emission. The main project objective is the detection of primordial gravitational waves by means of their B-mode signal in the polarized component of the power spectrum of the CMB, if it have an amplitude larger than r=0.05. Since B-modes are the imprint of primordial gravitational waves on the CMB, the information derived from this project would provide valuable information on the physics of the inflationary period, the epoch of exponential expansion in the primordial Universe, at the very beginning of our origins.

To achieve this aim, the instrumentation must be able to measure not only the CMB's polarized signal, but also the foreground emission sources. The frequency range chosen for the QUIJOTE Experiment comes from the fact that below 40 GHz the polarized signal due to thermal dust is very low. The important emission to take into account at these frequencies is that due to the synchrotron processes since the free–free emission, belonging to the electron–ion scattering in interstellar plasma, is an unpolarized signal because of the anisotropic and random nature of the scattering process.

The frequency distribution of the different emissions gives us the strategy to design the experiment. A first instrument measuring at the lower frequencies (10-20 GHz) of the experiment with enough sensitivity to detect astrophysical foreground emission (synchrotron and AME), and two other instruments working at the higher frequencies, centered at 30 and 40 GHz, to detect or constrain the imprint of B-modes down to r=0,05. This signal would be an extremely weak emission.

From these scientific objectives arise the special operational conditions required for the instrumentation. The frequency range set by the demanding observational requirements defines the three instruments that composed the experiment: the Multi Frequency Instrument (MFI) working from 10 to 20 GHz, the range where the synchrotron and anomalous emission are important, a Thirty GHz Instrument (TGI), and a Forty GHz instrument (FGI) at the higher frequencies of the experiment, where the influence of the thermal dust is still less noticeable with respect the synchrotron.

A cryogenic closed-cycle refrigerator achieving physical temperatures of 20 K for the cryogenic low noise amplifiers and the antenna feed hardware is needed to be able to detect the weak polarized signal coming from the CMB. Also, because of the weak signal, the 30 and 40 GHz instruments have been designed with a larger number of receivers. On the other hand, two telescopes will reduce the observing time needed to reach the specified signal-to-noise ratio (S/N), operating simultaneously with two of the three instruments, since the instruments must operate for a period of at least 3 years. Finally, as the microwave frequency band is observable day and night, a 24-hour working system must be strong and stable enough in the varying conditions of temperature and solar radiation between day and night.

These overall conditions have led the project to the adopted solution of two telescopes and three cryogenic instruments working in the range from 10 to 47 GHz.

More detailed information concerning the science goals of the project can be consulted in reference [1].

2. STATUS OF THE PROJECT

The QUIJOTE experiment is not just a single instrument, but the development of several instrumentation projects at the same time, since the installation is composed of five main systems. In this section we present the state of the instrumentation up to now. A previous report presenting the whole experiment and the progress of every system was published in the SPIE 2014 proceedings, reference [2].

2.1. Telescopes

The twin QUIJOTE telescopes (QT1 and QT2) are two altazimuthal offset dual-reflector antennas (figure 1). They move quickly (10 rpm) on top of an unlimited rotational system in the azimuthal axis. Electric power supplies, communications, and fluids go through a rotatory joint inside the telescope pedestal. This allows for continuous operation while meteorological conditions are favourable. The telescope can move from 28 to 90 degrees in elevation in the case of the QT1 and this range was extended from 25 to 90 degrees for the QT2 in order to be able to observe the galactic center. With these capabilities each telescopes can generate a map of the entire sky visible from the Teide Observatory (latitude 28º 18'), which means an approximate coverage area of 32000 sq. deg.

The primary and secondary mirrors are surfaces made in cast aluminium and placed in a crossed Mizuguchi-Dragone configuration, in order to minimize the cross-polarization levels and provide symmetric beams. The primary mirrors are paraboloids of 2.25 m aperture and the secondary mirrors have a hyperbolic shape with a 1.89 m aperture. The specification achieved for the mirror roughness (Ra ≤ 2 µm for QT1 and Ra ≤ 1.6 µm for QT2) gives working frequencies up to 100GHz for the QT1 and 200 GHz for QT2.

The principal operational modes of the telescope are the following: nominal mode, sky raster mode, horizontal raster mode, and pointing and tracking mode. In the nominal mode the telescope rotates continuously in azimuth at a fixed elevation, this movement in combination with the Earth's rotation generates a map of the region visible during observation. The sky raster mode explores a small rectangular region of the sky moving constantly in right ascension, while the declination is increased in a specified step after each scan. The horizontal raster is a similar mode although in telescope coordinates, scanning in azimuth with increasing in elevation. Finally, the pointing and tracking mode allows the telescope to aim at a given target and maintain it in the field of view. Also, there is a parking mode for placing both telescope axes in the parking position.

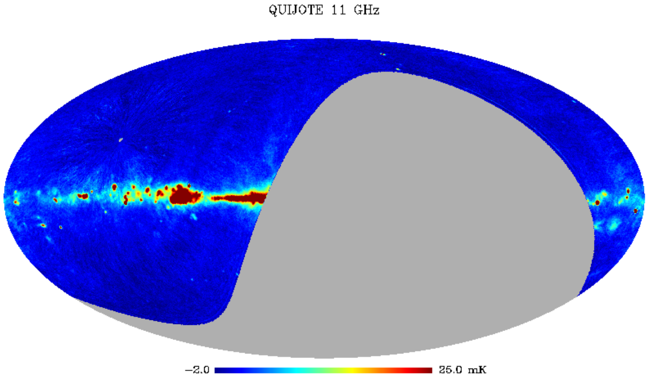

Figure 1 (left). QUIJOTE telescopes operating simultaneously with the MFI and the TGI instruments.

Figure 2 (right). Example of an intensity sky map at 11GHz made with a MFI survey in the QT1.

Both telescopes are already operating at the observatory. The QT1 began in November 2012, after the installation of the MFI. In view of the good results from the first telescope, the QT2 was designed and fabricated following the same design with some improvements and with a new specification to reach 200 GHz, with a view to a future instrument to be developed to work at this frequency. At the moment, the QT2 is also in operation with the TGI in its focus, which is being commissioned from May of this year.

More details about the QUIJOTE telescopes specifications, design, manufacture, verification test and integration on site, can be found in the references [3] and [4], and also at this SPIE Astronomical Telescopes + Instrumentation conferences 2016, in the upcoming article of reference [12].

2.2. Instruments

The two first instruments are already integrated in the focal plane of each telescope. The MFI has three-and-a-half years of operation on the QT1, and the TGI began its technical commissioning on the QT2 in May this year. The FGI is in the fabrication stage, and the first polarimeters are expected to be tested at the observatory before the end of 2016.

2.2.1. Multi-Frequency Instrument

The MFI was designed to observe simultaneously in several frequencies by means of four polarimeters. These chains receive in the central frequencies of 11.2, 12.9, 16.7, and 18.7 GHz, with a 2 GHz bandwidth covering the range from 10 to 14 and from 16 to 20 GHz, and each polarimeter gives eight outputs to feed the Data Acquisition System.

The opto-mechanics of the receiver comprises four partially cooled conical corrugated feedhorns, aligned with the other opto-mechanical components inside the cryostat. In the original configuration the feedhorns were followed by a rotating polar modulator, for the purpose of avoiding 1/f noise; however, after some time of operation, the rotating mechanics of the modulators showed a weak behaviour. For this reason, the modulators are currently being moved in discrete positions (0º, 22.5º, 45º, and 67.5º) with the exception of the first polarimeter, which is totally fixed.

On the other hand, the objective of removing the 1/f noise by means of the rapid rotation of the modulators was replaced by the integration of hybrid couplers in each polarimeter, giving correlated outputs in all four detectors. In more detail, a 90º hybrid coupler has been implemented just before the cooled LNA (Low Noise Amplifier) and another just after the warm amplification. In this way, both the Q and U signals contain the same 1/f noise and the difference gives 1/f cancellation. (See the updated receiver scheme in figure 3).

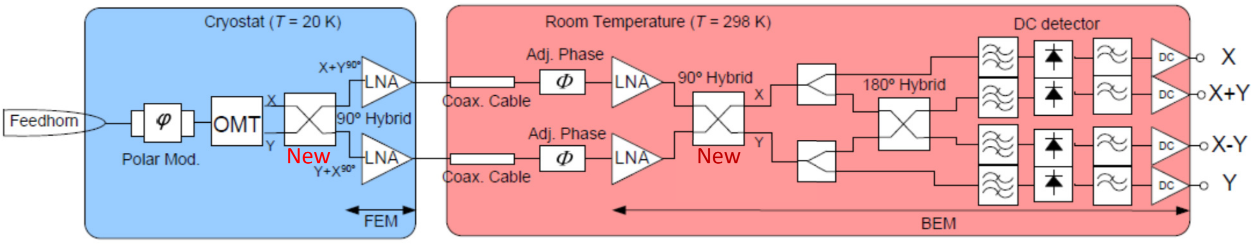

Figure 3. MFI receiver schematic diagram with the new hybrids implemented.

Also, a failure in one of the LNAs of the fourth receiver made us replace both amplifiers by new ones with higher gain and lower noise; because of this change, the gains from horn 4 have increased approximately by a factor 2.

Among the improvements to be carried out in the next MFI stage, the most important one is the replacement of Caltech 8–18 GHz cryogenically cooled LNA. New more sensitive amplifiers are already available in the market. Since the LNA is a critical part of the polarimeter design, any improvement in this device will provide a significant improvement in the data.

The MFI (figure 4) has accumulated around 14,000 hours of observing time, including observations of three cosmological fields (which cover around 3,000 deg2), and several galactic fields (molecular clouds, supernova remnants, etc.). Also a wide survey map covering 20,000 deg2 (see figure 2). Some scientific results coming out of these data have been published in references [10] and [11].

A complete description of the Multi-Frequency Instrument and its functionality, as well as the control system, can be seen respectively in references [5] and [6].

2.2.2. Thirty GHz Instrument

The second QUIJOTE instrument installed at the observatory is the Thirty GHz Instrument, centered at the frequency of 31 GHz, with a bandwidth of 10 GHz. The signal is received simultaneously by means of 30 identical polarimeters that feed the Data Acquisition System with four channels each. The receiver design is not based on the rotating modulators, since this solution was found to be not robust enough for a long-term operation system such this; instead, a polarizer opto-mechanic element was designed and manufactured for this frequency. The combination of two phase-switches with two possible phase different states, one at 0º/90º and other at 0º/180º, generates four polarization states, minimizing several systematics. (See reference [9] for further information about phase-switch design).

Although the original cryostat design contained 31 polarimetric chains, one of the polarimeter sites had to be used to insert a set of extra thermal links, needed to achieve the 20 K specified as the LNA working temperature. This temperature is one of the more important requirements of the cryostat design, since the weaker detectable signal depends directly on this temperature; therefore, a considerable effort was invested in the LNA thermal link design. This element design is based on an automatic thermal link concept consisting of a crown-like cylindrical copper of 12 fingers, with a Teflon clamping ring. Detailed description of the TGI cryo-mechanics can be found in a forthcoming refereed article [13]).

The receiver, or polarimetric chain, is formed by a cryogenic part called Front-End Module (FEM) fitted inside the cryostat, and a room temperature Back-End Module (BEM). The FEM unit consists of the following elements connected in series: a feedhorn, a polarizer, an OMT, and two cryo-LNAs connected in parallel by means of twisted wave-guides guides to the OMT outputs. The FEM power supply is arranged in three rack units attached to the back side of the cryostat. The BEM unit has two gain and filtering modules, a phase-switch module, and a correlation and detection module. Two racks hold the thirty BEM units and these racks are attached to both sides of the cryostat can. See reference [8] for a detailed report on the TGI receiver.

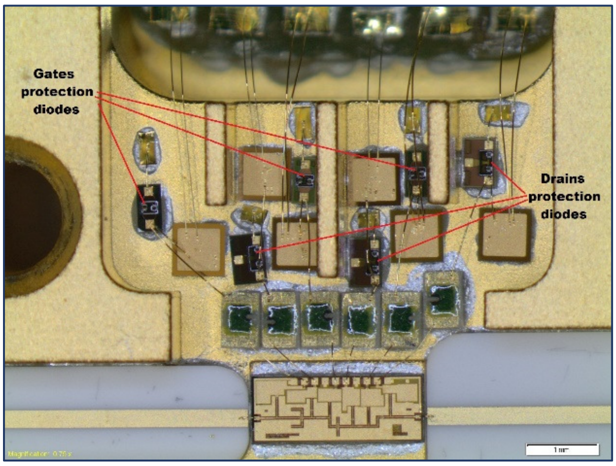

Figure 4 (left). MFI in operating on the QT1 telescope.

Figure 5 (right). A detail of the LNA inner assembly. Protection diodes in the gates and the drains are marked with red lines. The MMIC chip is shown at the low part of the image.

The TGI cryo-LNAs were designed and assembled by DICOM using 100 nm mHEMT MMIC chips supplied by the IAF-Fraunhofer Institute for Applied Solid State Physics, and 130 nm mHEMT MMIC devices supplied by the OMMIC Company, one for each of the 60 LNAs, since two LNAs are assembled in every polarimetric chain. The internal LNA DC circuit for the IAF MMIC includes protection diodes at gates and drains connection points (MA4E1319 for drains and MA4E1318 for gates). This measure was adopted after some problems occurred during the test phase.

Another important subsystem of the instrument is the Data Acquisition System (DAS), which has placed specifications on the sampling frequency, the switching frequency, and the synchronization of the signal. The data coming from the four channels of each of the 30 polarimeters are acquired and processed in real time. This pre-processing, done by the dual-core PXI-8109 embedded processor of the DAS, allows the system to manage and store the large data rate. The 120 channels are sampled simultaneously at 160 kHz and synchronized with the phase-switch commutation signal and with the telescope signal. Finally, the data are sent to an external terminal to be stored. The development is based on an NI PXI-1044 system with eight PXI-4495 acquisition modules; for synchronization tasks, we use a TimeSync sNTP for the telescope and RIO PXI-7813R modules for the phase-switches. The software is developed in Labview 2013 with a simple and flexible QMT (Queued Message Handler) architecture (a detailed description of the TGI Control System can be found in a forthcoming refereed article [14]).

The large amount of temperature sensors attached to the various elements inside the cryostat led us to develop a specific temperature monitoring system. The design of this T control and monitoring system, named PLT-HPT-32, has been a significant part of the work on the project. The developed system can acquire the temperature data of 32 sensors, with a resolution below of 0.1 K in the range of 16 to 320 K. In addition, data are shown in a screen, providing also a status information of every channel, like alarms, relays and time. Finally, the system can be remotely monitored by a network, using an Ethernet port. The PLT-HPT_32 system is presented in reference [15].

Most part of the fabrication was finished at the end of 2014. The assembly, integration, and verification (AIV) tasks were carried out during the first half of 2015, and the first tests at the observatory were performed by the end of June 2015. During this phase, a serious failure in the cryo-LNAs occurred; exactly 11 units of IAF-Fraunhofer MMIC chips were damaged because of some transient peaks in the voltage provided by the FEM DC power supply unit. The chips had to be replaced inside the LNAs by new ones. To avoid breaking more chips, the instrument was moved back to the IAC laboratory in order to remove the LNAs from the polarimeters and to install protection diodes in the MMIC, in antiparallel circuit for the gates and in series for the LNA drains (figure 5). In addition, a DC voltage regulator circuit with delayed switch-on operation was integrated in the FEM rack, before the power supply goes into the amplifiers. These safety actions have given excellent results up to now.

Another difficulty found during laboratory tests is the detection of a strong dependence of the phase on ambient temperature, particularly with the BEM rack temperature. This fact has forced us to develop and implement a temperature control subsystem of the BEM racks with the purpose of stabilizing the phase response of the module. This rack currently controls temperature within a range of 35ºC ± 0.1 ºC at the laboratory, which provides adequate stability for the TGI phase response in a typical observation time of several hours. In order to minimize the ambient temperature fluctuations even more, a cover for the entire instrument is now being designed.

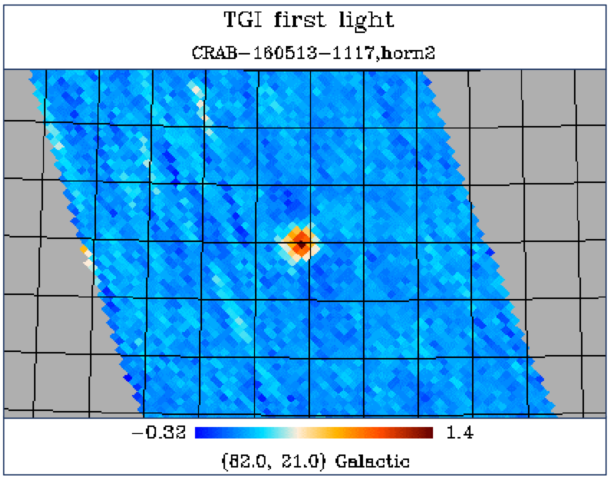

Figure 6 (left). TGI being installed in the QT2 focus.

Figure 7 (right). An intensity map of CRAB region done with one of the three TGI polarimeters that are being tested at the Teide Observatory.

The instrument was installed at the telescope focus in April 2016 (see figure 6); since then, sky calibration and tests have been performed up to the present time. To avoid risks on MMIC chips, the TGI has only three polarimeters installed (which means six LNAs), and the other 27 units will be integrated when preliminary tests on the three polarimeters have successfully concluded. With this configuration, technical first light was obtained in 12 May this year (figure 7), when several polarized sources in the sky, including the Crab Nebula, were observed.

See also previous articles on the TGI design and manufacture in references [7] and [2], and related forthcoming contributions in references [13], [14], and [15].

2.2.3. Forty GHz Instrument

The third QUIJOTE instrument will extend the frequency range of the experiment by observing at 40 GHz. More specifically, the FGI central frequency is 41 GHz with a bandwidth of 12 GHz. The whole instrument design is analogous to that of the TGI, and the same number of polarimetric chains make up the system with thirty receivers. In fact, the chains have been scaled to fit in the same space and footprint as the TGI chains in such a way that the same cryostat will be used for the two instruments. This strategy has been possible owing to the modular design of the cryostat, where the cryogenic part of the polarimeter (FEM) can be easily removed and replaced, one by one. Other auxiliary equipment and subsystems will be also used for both the TGI and the FGI, as well as the Data Acquisition System.

After a period of prototype design, manufacture, and tests, the system is now totally defined and in the fabrication process. Most of the commercial elements, such as wave-guides, flanges, coaxial adapters, cryo-harness, semi-rigid coaxial cables, etc., have been already acquired. Moreover, the opto-mechanics of the FEM is being manufactured at the IAC workshop, except for some pieces involving specific fabrication process, such as electro discharge machining (EDM), which is the case for orthomode transducers and polarizers that have been manufactured by the UTILMEC Company (Cantabria, Spain). These opto-mechanical elements have been assembled in the laboratory and tested at microwave level, and have given excellent results.

The devices integrating the BEMs, designed by DICOM team, are already being assembled at the DICOM laboratory, as well as the LNAs assembly. The LNAs for the FGI are based on two cascaded 100 nm MMIC chips provided by the IAF-Fraunhofer (Fraunhofer Institute for Applied Solid States Physics), with an equalizer in between. Results from prototype tests are totally successful.

The first chains, both for the opto-mechanics and BEM components, could be assembled after summer this year, with the aim of being integrated and tested in the cryostat at the observatory before the end of the year.

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