

QUIJOTE – CMB experiment: a technical overview

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ABSTRACT

The QUIJOTE-CMB experiment (Q-U-I JOint TEnerife CMB experiment) is an ambitious project to obtain polarization measurements of the sky microwave emission in the 10 to 47 GHz range. With this aim, a pair of 2,5m telescopes and three instruments are being sited at the Teide Observatory, in Tenerife (Canary Islands, Spain). The first telescope and the first instrument (the MFI: Multi Frequency Instrument) are both already operating in the band from 10 to 20 GHz, since November 2012. The second telescope and the second instrument (TGI: Thirty GHz instrument) is planned to be in commissioning by the end of summer 2014, covering the range of 26 to 36 GHz. After that, a third instrument named FGI (Forty GHz instrument) will be designed and manufactured to complete the sky survey in the frequency range from 37 to 47 GHz. In this paper we present an overview of the whole project current status, from the technical point of view.

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

1. INTRODUCCION

The QUIJOTE-CMB experiment is a European collaboration conformed by the Instituto de Astrofísica de Canarias, the Instituto de Física de Cantabria, the IDOM company, and the Universities of Cantabria, Manchester and Cambridge, and led by the Spanish collaborator. The main objectives are the polarization measurement of the extragalactic emission and the Cosmic Microwave Background (CMB) in the frequency range of 10–40 GHz. After three years of effective observations, it is expected that the data obtained by the two telescopes and the instruments will have the required sensitivity to detect evidence of primordial gravitational-wave in the CMB polarization (B modes), if the tensor-to-scalar ratio is larger than $r = 0,05$. The measurement of the CMB polarization by mean of QUIJOTE has a great cosmological relevance because it would provide us a direct test of the inflationary theory of the early Universe. More specific details about the scientific goals of the project can be found in the reference article [1].

The experiment is located at the Teide Observatory in Tenerife (Canary Islands, Spain) and it is composed of two telescopes and three instruments. Presently, the first telescope and the first instrument are in the scientific exploitation phase. The second telescope is being installed at the Observatory, and the second instrument is in the integration stage at the IAC (Instituto de Astrofísica de Canarias), in Tenerife. There is a third instrument designed and tested at prototype level, of which the manufacturing is expected to start before the end of 2014.

2. THE TELESCOPES: QT1 & QT2

The first QUIJOTE telescope (QT1) was installed at the observatory in May 2012 and after several months of commissioning and control adjustments to improve the pointing model, user interface, etc., began its operation in November 2012, after the installation and the beginning of the first QUIJOTE instrument commissioning, the MFI.

The QT1 is an alt-azimuthal off-axis microwave telescope which can rotate around the AZ axis with a maximum velocity of 0,25Hz. The mirrors are disposed in a cross-dragonian design, with a parabolic primary mirror size of 2,25m of aperture and a 1,9m hyperbolic secondary mirror, manufactured in cast aluminium under the specification of $Ra \leq 2\mu\text{m}$ with a maximum deviation of 100 μm , a requirement set for the measurement of a maximum frequency of 90 GHz. All the signal and electrical supplies, like the electrical power and fibre-optics for control communication, are passed through a rotating joint to the rotating parts of the telescope and the instrument, whereas the equipment needed for the compressed Helium supply for the instrument cooling system, are attached to the rotating telescope mount.

The requirements of the telescopes come from the performances of the main observing modes. The **Nominal Mode** is a fast azimuth rotation at fixed elevation while Earth rotation provides daily sky coverage of several thousand square degrees, giving a local map of the full available sky, a full map can be produced in 3 hours, covering elevations from 30° to 90°. The **Sky Raster and Horizontal Raster Modes** scan a rectangular area at constant velocity on right ascension or azimuth, respectively, generating a few square degrees maps (typical 10° x 10°) of particular regions containing cosmological fields, calibrators, galactic fields, etc. Also the **Pointing and Tracking Mode** allows the telescope to point to an object in the sky which is tracked for a long period of time, such as point sources which may be used as calibrators.

The telescopes are designed to optimize the cross-polarisation (lesser than -35dB) and to provide symmetric beams. Also, the system is under-illuminated to minimize side-lobes and ground spillover. Actually, after one year of operation, an extension of the telescope anti-radiation screen has been installed to minimize even more the side-lobes and to avoid the reflections at 11 and 13GHz, coming from the geostationary satellites. Details of the QT1 design, fabrication and installation can be found in the reference [2].

Table 1. QUIJOTE telescopes main performances.

	QT1	QT2
Mount	alt-azimuthal	alt-azimuthal
Azimuth maximum rotation velocity	15 rpm	10 rpm
Maximum zenith angle	60°	65°
Primary mirror projected aperture	Parabolic 2,25m	Parabolic 2,25m
Secondary mirror projected aperture	Hyperbolic 1,89m	Hyperbolic 1,89m
Mirror roughness R_a	2 μ m	1,6 μ m
Mirrors roughness (rms)	$\leq 100\mu$ m	$\leq 100\mu$ m

The second QUIJOTE telescope (QT2) is a replica of QT1, with some improvements in order to produce a new system that will be able to operate up to 200GHz, in the view of possible future extensions of the project. The contract for its design, fabrication and installation was awarded early 2013 to IDOM Company (Bilbao, Spain), which is the same manufacturer enterprise of the first telescope. The kick-off meeting took place in June 11th, 2013, and a first review to consolidate the conceptual design was achieved in June 26th, 2013. The Critical Design Review (CDR) meeting was successfully passed in September 9th – 26th, 2013. The construction started immediately after the CDR meeting, and currently the telescope has been already assembled, integrated and tested at the main IDOM manufacturer subcontractor facilities. The telescope will be finally accepted at the Teide Observatory in July 2014 after passing on-site acceptance tests. A detailed description of the QT2 by the manufacturer company can be obtained from another presentation of this congress, see reference [3].

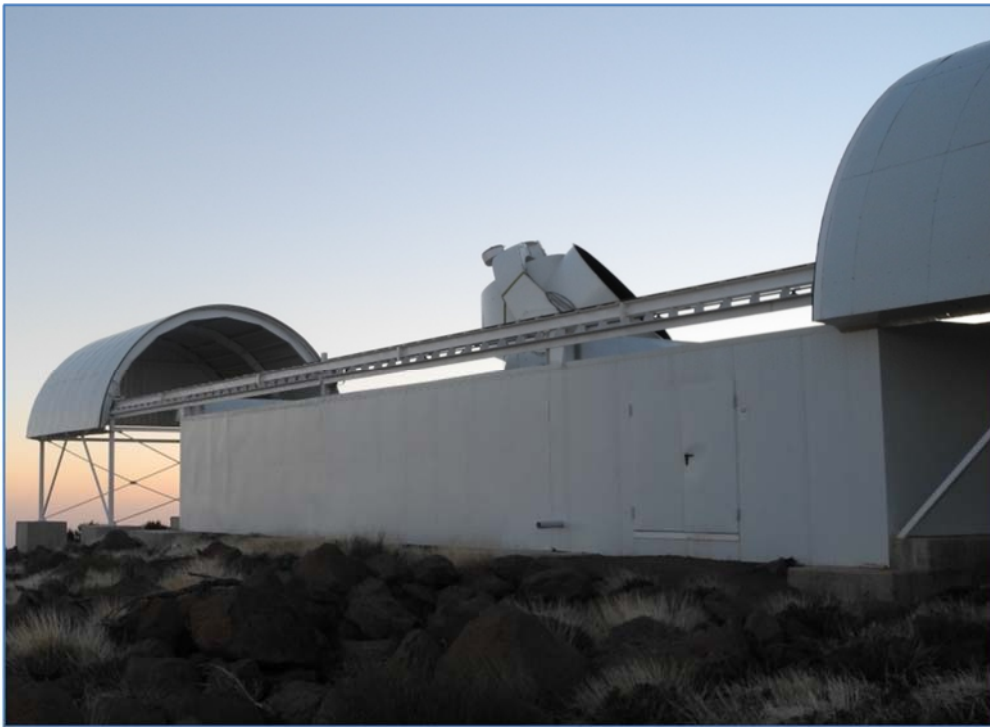


Figure 1. QT1 and MFI operating at the Teide Observatory.

3. INSTRUMENTATION

3.1. Multi-frequency instrument (MFI)

The MFI first light occurred in November 2012, and the commissioning period was finished in May 2013, when the scientific operation phase started. During this phase, the instrument has operated 24 hours per day with an observing efficiency (accounting for bad weather and technical time losses) of 71%. The main science driver for the MFI is the characterization of the Galactic emission. The accumulated data in several galactic regions have quality to be presented in first release of papers of the project during 2014.

The MFI is a multi-channel instrument with four independent polarimeters to observe at 11, 13, 17 and 19GHz. The instrument was initially designed with five chains of polarimeters although the central one, corresponding to the frequency of 30 GHz, had to be removed and also a more powerful cool-head was used in order to increase the cooling power of the cryostat and in this way assure the temperature range needed inside the can. The original MFI five chains design is described in reference [4].

Every polarimeter chain is formed by a conical corrugated horn that feeds a cryogenic on-axis rotating polar modulator which can rotate at a speed of up to 1Hz. The polar modulator purpose is to derive linear polar parameters Q, U and I and switch out various systematics. The detection system provides optimum sensitivity through two correlated and two total power channels, thanks to the MMIC 6-20GHz Low Noise Amplifiers with a gain of 30dB and noise temperature of <10K. The system has been calibrated using bright polarized celestial sources and also through a secondary calibration source and antenna.

The acquisition system, telescope control and housekeeping are all linked through a real-time gigabit Ethernet network in the following structure: an LXI-VXI bus is used for the signal acquisition system, an EtherCAT bus implements software PLCs developed in TwinCAT to perform the polarimeters motion and the telescope two axes. The time stamp is synchronized to a GPS time signal, implementing the Precise Time Protocol-1588 which provides synchronization to less than 1 microsecond. The user interface is written in LABVIEW. A complete description of the MFI Control System can be consulted in the reference article [5].

Main racks and electronics elements of the instrument are integrated in two cabinets attached to the telescope structure, as well as the auxiliary cooling equipment to maintain the cryostat at the required temperature.

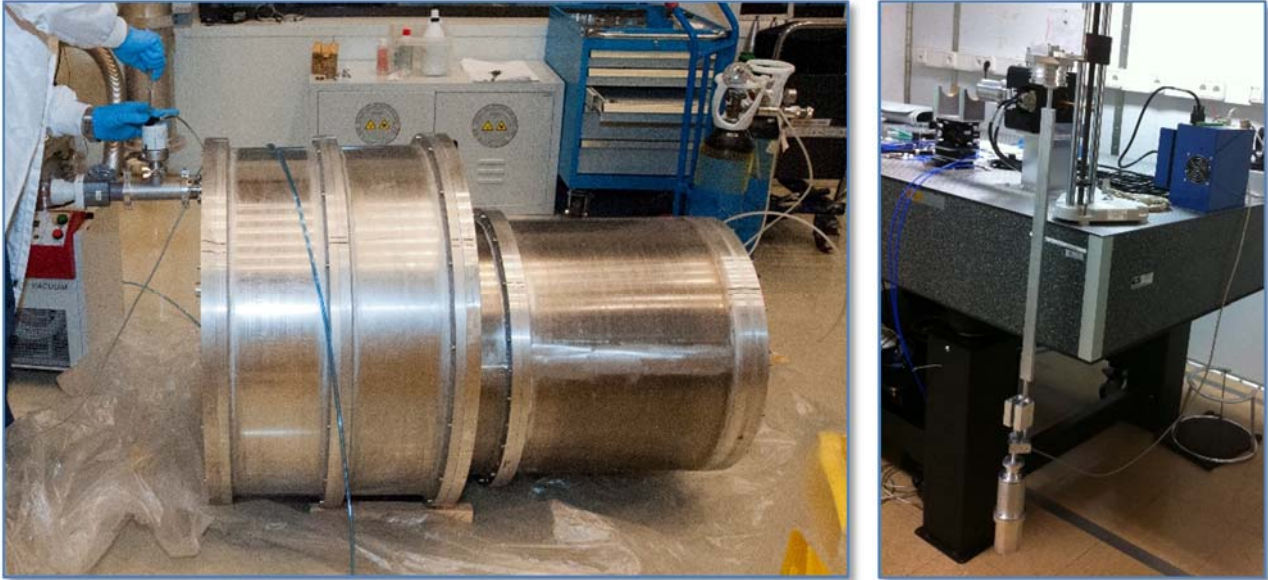
3.2. Thirty GHz instrument (TGI)

Unlike the multi-frequency MFI, the TGI was conceived to observe exclusively in the 26–36GHz frequency band. It was initially conceived to have 15 polarimeters, but as the design was studied and developed in more detail this number was increased. Finally the design was frozen with 31 chains, in this way the scientific objectives can be reached in about two-thirds of the planned time.

TGI polarimeters are based on a different concept than those of the MFI ones. They do not have rotating polar modulators, since the system was not considered appropriated for the long-term operation required for the TGI. The new concept is based on a fixed polarizer combined with two phase switches of 90° and 180° working at room temperature and in the direct correlation of the microwave signals.

The receiver's opto-mechanics are composed by a high directivity corrugated horn, followed by a polarizer and an ortho-mode transducer (OMT), which split the electromagnetic wave into two orthogonal circular polarizations components (RHC and LHC). The next element is the Cryogenic Low Noise Amplifier (LNA) which has been designed using

mHEMT (metamorphic High Electron Mobility Transistor) technology of 100nm, provided by the Fraunhofer Institute of Freiburg (IAF), in Germany. Most part of the components are already manufactured (there are components available to complete 16 pixels) and the assembly of the polarimeters chains began on June 2014. See all details about the TGI design and microwave laboratory measurements in reference [5].



Figures 2 & 3. Cryostat vacuum can, leaks tests at the IAC. Polarimeter chain prototype.

The current status of the TGI cryostat subsystem is the following: the vacuum can was built in Manchester University and arrived to the IAC on July 2013. After solving some minor problems and leaks, the cryogenic tests were successfully passed. The detailed design of cold plates, thermal links, shields, etc, were finished at the IAC mechanical and drawing divisions, and all the pieces are already under manufacturing process.

The acquisition data system have been developed and it is being tested with its basic functionality in a calibrator test bench, where a single pixel is being essayed in order to check the proposed calibration procedure, as well as to test the electronic racks of the modules (see reference [5]). The instrument electronic cabinets are also being assembled. The aim of the engineering team is to install the instrument on the telescope QT2 just after summer 2014.

3.3. Forty GHz instrument (FGI)

The third QUIJOTE instrument is based on the same polarimeter concept as the TGI, moreover, the whole FGI has been designed in such way that the cryostat can must be identical to the TGI. Therefore, the can of the FGI cryostat does not have to be redesigned. There are also others FGI subsystems that have been developed in accordance with the TGI design, such as the data acquisition system, the racks containing the DC bias cards, and the test cryostat. On the other hand, since the chains are modular in both instruments, the design of the FGI polarimeters has been adjusted to fit within the same footprint than the TGI chains, therefore polarimeters from the two instruments would be exchangeable.

The number of polarimeters is 31, the same as the TGI, although in this case they are working at 41GHz with 10GHz bandwidth. The opto-mechanical parts: feed-horn, polarizer and ortho-mode transducer, are already fully designed and

several prototypes have been tested. The cryogenic LNA, which is a critical subsystem of the receiver, has been developed and some prototypes have been designed and tested using one MMIC, 100 nm mHEMT technology from IAF-Fraunhofer (Germany), followed by a hybrid stage with one transistor. Prototypes phase switches of 180° and 90° have been designed and tested with two different alternative technologies (rectangular waveguide or microstrip line circuits). In order to reduce the size, weight and cost of the correlation and detection module, several prototypes have been built and tested using Substrate Integrated Waveguide (SIW) technology. The objective is to use cheaper and more reproducible modules, to avoid the high cost and long manufacturing time needed for modules based on rectangular waveguide technology. The alternative technologies would permit an easier and faster manufacturing in series.

The status of this third instrument is the following: a prototype of a complete receiver chain has been completed, using classical rectangular waveguide technology for the phase-switches modules and for the correlation and detection modules, although the manufacturing has not already started.

Table 2. Nominal specifications of the three QUIJOTE instruments: MFI, TGI and FGI.
Sensitivities are referred to Stokes Q and U parameters.

	MFI	TGI	FGI
Nominal Frequency [GHz]	11 13 17 19	30	40
Bandwidth[GHz]	2 (each)	8	10
Number of horns	4	31	31
Channels per horn	8	4	4
Beam FWHM [°]	0,92 0,92 0,60 0,60	0,37	0,38
T_{sys} [K]	25	35	45
Sensitivity [Jy s^{1/2}]	0,42 0,59 0,44 0,54	0,06	0,06

3.4. Test-cryostat

The Test Cryostat is a smaller device where three chains can be integrated and tested simultaneously, before being assembled in the final cryostat. Chains tests will be performed for the TGI polarimeters as well as for those of the FGI.

There are several advantages of manufacturing this test-cryostat. One advantage comes from the complexity of doing tests in the final cryostat, due to its dimensions and consequently the time needed to cool down and warm it for every test to be performed. The test cryostat will allow checking more quickly and efficiently the manufactured chains, detecting any possible failures before installing the chains in the final system. On the other hand, the pieces to build this cryostat were recovered from an old project, so the cost of the final device was very low, not taking into account the amount of engineering time that has been invested.

Furthermore, the test cryostat is playing an important role in testing some design solutions of critical elements, like the design proposed for the thermal links for each polarimeters. This element is a crown-shaped piece with 12 fingers which are bound by a teflon ring that contracts more rapidly than the copper (or Al) crown when is cooled, pressing the fingers against the polarimeter which is inside. A model of this crown and a graphic of the differential contractions between teflon and cooper (or Al) is shown in figure nº 4.

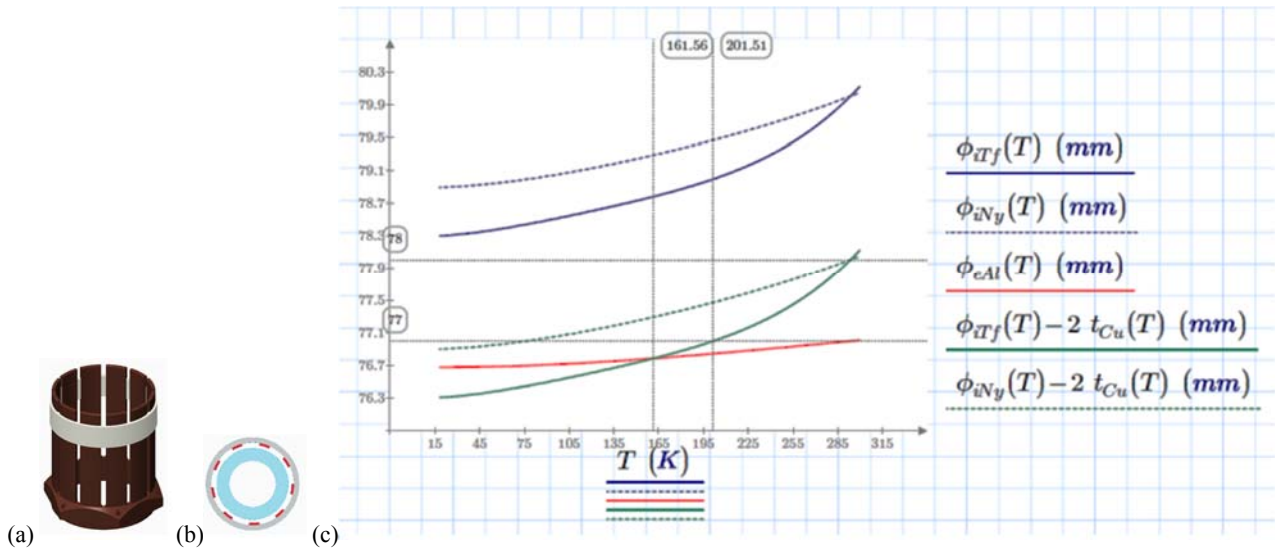


Figure 4. (a) Crown: polarimeter thermal links. (b) Crown transversal section. (c) Thermal behaviour of different studied materials (Teflon, Nylon, Aluminium, Copper ETP / OFHC).

The test-cryostat has been fully assembly, integrated and tested and the next step is the integration and testing of the first pixel. After that, the functional tests of all the pixels, three by three, will begin.



Figure 5. Assembly of the QUIJOTE test cryostat at the IAC AIV room. Sensitivities are referred to Stokes Q and U parameters.

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