



Report ITU-R RA.2512-0
(10/2022)

**Technical and operational characteristics of
broadband, background-limited detectors
operating in the millimetre-wave regime**

RA Series
Radio astronomy



Documents
Document Sharing Hub

Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

The regulatory and policy functions of the Radiocommunication Sector are performed by World and Regional Radiocommunication Conferences and Radiocommunication Assemblies supported by Study Groups.

Policy on Intellectual Property Right (IPR)

ITU-R policy on IPR is described in the Common Patent Policy for ITU-T/ITU-R/ISO/IEC referenced in Resolution ITU-R 1. Forms to be used for the submission of patent statements and licensing declarations by patent holders are available from <http://www.itu.int/ITU-R/go/patents/en> where the Guidelines for Implementation of the Common Patent Policy for ITU-T/ITU-R/ISO/IEC and the ITU-R patent information database can also be found.

Series of ITU-R Reports

(Also available online at <http://www.itu.int/publ/R-REP/en>)

Series	Title
BO	Satellite delivery
BR	Recording for production, archival and play-out; film for television
BS	Broadcasting service (sound)
BT	Broadcasting service (television)
F	Fixed service
M	Mobile, radiodetermination, amateur and related satellite services
P	Radiowave propagation
RA	Radio astronomy
RS	Remote sensing systems
S	Fixed-satellite service
SA	Space applications and meteorology
SF	Frequency sharing and coordination between fixed-satellite and fixed service systems
SM	Spectrum management

Note: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.

Electronic Publication
Geneva, 2022

© ITU 2022

All rights reserved. No part of this publication may be reproduced, by any means whatsoever, without written permission of ITU.

REPORT ITU-R RA.2512-0

Technical and operational characteristics of broadband, background-limited detectors operating in the millimetre-wave regime

(Questions ITU-R 226-2/7 and ITU-R 257/7)

(2022)

1 Introduction

The cosmic microwave background (CMB) is a pervasive cold glow across the entire sky at microwave through millimetre-wave frequencies. Studying this cosmic signal informs our understanding of the Universe and has motivated the development of extremely sensitive millimetre-wave bolometric detectors and others with similar characteristics, with large fractional bandwidths of order 30% or more. Here, these detectors are referred to as background-limited because when cooled to sub-Kelvin temperatures, they achieve sensitivities that are limited only by the Earth's atmosphere. These detectors are placed on telescopes at the best millimetre observing sites on Earth, which have exceptionally low atmospheric loss. Cosmological surveys with background-limited detectors at these sites normally require years of integration time to achieve their measurement goals.

The CMB is now understood to be the relic radiation of the hot big bang associated with the origins of the observable universe, cooled through its subsequent expansion. The Nobel-prize winning discovery of the CMB in 1965 [1], was achieved through careful analysis of excess sky noise observed with a single microwave receiver at a single frequency, carefully analysed to eliminate both natural and artificial foreground radiation. Since then, the field has advanced dramatically, from first tracing out the near-perfect Planck spectrum corresponding to blackbody radiation at a thermodynamic temperature of 2.7 K [2], [3], to mapping the angular structure of the tiny variations in temperature across the sky to reveal structure in remarkable agreement with cosmological theory [4] to [8].

Observations with small telescopes onboard satellites and stratospheric balloons have been key for these observations at few-arcminute to few degree angular scales. Further progress in the field now requires observing fainter signals with better instrumental sensitivity and angular resolution, requiring large telescopes (6-metre class) which are difficult to deploy in space or on balloons. Hence, multiple ground-based telescopes are required, with broadband bolometers operating at background-limited sensitivities limited only by noise from atmospheric emission. To reach nano-Kelvin sensitivity levels, these telescopes are equipped with tens of thousands of broad-band bolometric detectors, observing patches of sky at millimetre to centimetre wavelengths for several-year surveys [9], [10]. Cosmological observations provide steadily increasing insight into the astrophysics of the early universe, and test fundamental physical theory at energy scales inaccessible to high-energy physics experiments on Earth. While all observations are generally compatible with the same overall cosmological model, this model requires the Universe to be filled with matter and energy of unknown forms, dubbed dark matter and dark energy, amounting to 95% of the total density [11]. It is also believed that when the Universe was just a fraction of a second old, it underwent a period of ultra-rapid expansion, called cosmic inflation, driven by physical processes yet poorly understood, during which in about 10^{-32} seconds the size of the Universe was multiplied by a factor of at least 10^{26} [12]. Modern CMB observations are key to confirming this hypothesis, and provide essential information about the nature of dark matter and dark energy.

Because these cosmological surveys must repeatedly survey the sky each day and night for years to gain the requisite sensitivity, CMB observations are also creating a new window on the time-varying universe. With wide bandwidth and large sky coverage, these surveys are capturing rare, faint, or short-lived events that have previously gone unnoticed. Advances in instantaneous sensitivity enabled

by increasing detector counts and wider fields of view are further opening the discovery space to investigate transient and time-variable phenomena.

Recommendation ITU-R RA.769 considers “...that radio astronomers have made useful astronomical observations from the Earth’s surface in all available atmospheric windows ranging from 2 MHz to 1 000 GHz and above...” and indeed, the achievements of modern CMB experiments would not be possible but for the passive use, from remote locations, of spectrum allocated to active services. The characteristics of CMB detectors are somewhat different from the RAS observatories covered in Recommendation ITU-R RA.769 in ways that render them both more and less susceptible to terrestrial radiation [13]. On the one hand, CMB detectors typically employ large fractional bandwidths (of order 30%), use detectors carefully designed to operate at background-limited sensitivity, and accumulate years of data to integrate down to high sensitivity. The typical bandwidth of such detectors in the millimetre-wave is an order of magnitude larger than the relatively small bandwidths assumed in Recommendation ITU-R RA.769. It should also be noted that the RAS thresholds covered by Recommendation ITU-R RA.769 are calculated on the basis that a typical observing bandwidth is at most 8 GHz, which is in stark contrast to what typical bolometric detectors offer (50 GHz and more), limited by the spectral width of atmospheric windows between strong absorption features of water vapor and oxygen. On the other hand, the sidelobe suppression, scan strategies, use of multiple wave bands, and analysis techniques all needed to reject natural foregrounds in CMB experiments can help mitigate artificial foregrounds as well. Antenna sidelobes, in particular, are much more a problem for CMB measurements than they are for classical radio astronomy, as the CMB requires much higher sensitivity observations, and contributions from the side-lobe irradiation play a crucial role.

This document aims to record the geographic sites, the RAS allocations utilized for CMB experiments, instrument characteristics of the bolometric cameras used in CMB experiments, and to provide background for further study and recommendations analogous to Recommendation ITU-R RA.769.

2 Sites

The needs of CMB experiments have driven them to be located at dry, high-altitude sites with minimum atmospheric absorption and access to parts of the sky with low astrophysical foreground emission. Ground-based telescopes observing in the millimetre-wave typically observe within atmospheric windows defined by absorption from molecules including oxygen and water in the Earth’s atmosphere. At exceptionally dry, high altitude sites, these atmospheric windows (shown in Fig. 2, and detailed in Table 2) have extremely low atmospheric absorption loss in typical weather.

In accordance with Recommendation ITU-R RA.769-2, these CMB experiments have been placed in geographically remote locations, which are “as free as possible from interference.” This Report will assist those Administrations seeking to afford protection to these experiments, following Recommendation ITU-R RA.769-2 which states, “that administrations should afford all practicable protection to the frequencies and sites used by radio astronomers in their own and neighbouring countries and when planning global systems”.

Current experiments sponsored by the United States and other administrations operate at the South Pole in the protected dark sector, and in the high Atacama Desert in northern Chile in the protected astronomical reservation under the jurisdiction of the Government of Chile. CMB experiments have also operated from Antarctic long duration balloon flights, which are not limited by atmospheric windows, and can achieve sensitivities significantly lower than described here, due to the reduced atmospheric noise at float altitudes.

The quality of these sites for millimetre-wave observations, including the magnitude of atmospheric emission noise and absorption and the resulting instrument sensitivity, is set by the precipitable water