Thermal Design and Thermal Behaviour of Radio Telescopes and their Enclosures

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by

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Springer

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Cover Picture: Plateau de Bure 15–m telescopes (France). The telescope in the foreground is partly assembled, the rear cladding and the panels are lacking; the pedestal, fork mount, secondary focus cabin, the CFRP–steel backup structure and the quadripod with subreflector are seen. The telescope in the background has the first generation panels with good specular reflection of visible light. The image in the reflector aperture is the inverted scenery of Plateau de Bure.

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Foreword

Every antenna, even those restricted to nighttime operation, is subject to thermal distortion. The greater the degree of surface precision demanded, the greater the relative importance of these distortions. Here again, the usual approximations are likely to be inadequate, and a computer analysis may be necessary. The choice of configuration of the antenna structure should minimize distortions due to temperature differentials in the structure and to changes in the ambient temperature. Consideration should be given to the use of reflective paints, and (for enclosed antennas) to environmental control. Lightweight insulation may be applied in some cases.

H. Simpson (1964)

Four hundred years ago, in 1609, Galileo used an optical telescope to observe the night sky. He saw objects and studied phenomena none had ever seen before. His discoveries mark the beginning of a new era in astronomy that is on the one hand the oldest science, and on the other the one which benefits most from modern technological breakthroughs. Recent examples are the fascinating discoveries made with modern optical telescopes like the Hubble Space Telescope, the ESO Very Large Telescope in Chile and a number of 8 to 10 metre telescopes on Hawaii. Radio astronomy, which exploits the second 'window' of the Earth's atmosphere through which we can observe and study cosmic phenomena, has had since its beginning a similarly revolutionary impact on our picture of the Universe.

The first evidence of cosmic radio signals was found accidentally more than 75 years ago when Karl Jansky detected with his communication antenna unexpected 'noise signals' and recognised that they must originate outside the Earth's atmosphere. Only a few years later, Grote Reber built the first dedicated radio telescope, a parabolic reflector of 10 metre diameter equipped with a receiver for 1.9 metre wavelength. In the short space of time, from this first prototype to todays radio telescopes, incredible developments have taken place driven by the wish to detect ever fainter signals, to extend the observations from the longest to the shortest wavelengths observable from the ground, and by the need to increase the angular resolution of radio telescopes by making the single aperture telescopes larger and by constructing multi-element radio interferometers. Today, radio astronomy exploits the entire radio window of the Earth's atmosphere from the microwave region to wavelengths of tens of metres. The ambitious goals of modern radio astronomy pose special challenges to the conceptual design and the construction of the current and future generation of radio telescopes.

Radio astronomy plays a significant role in the study of the Universe. During the early years of radio astronomy one focus was on the non-thermal continuum emission from relativistic electrons that interact with cosmic magnetic fields and emit radiation like the electrons in a synchrotron particle accelerator. Synchrotron radiation is emitted by our own Galaxy and many other galaxies, some of which, the so called radio–galaxies, are particularly bright. Another focus was on the observation (from on 1951) of the hyper-finestructure line of atomic hydrogen at a wavelength of 21 cm. Hydrogen is the most abundant element in the Universe and the observability of this line was predicted in the 1940s. The line carries information about the physical state of hydrogen in our own Galaxy and in different parts of the Universe, and by measuring its radial velocity shift with respect to the rest wavelength it also allows to derive kinematical information and from this, together with a galaxy model, structural information. As a result, the first three-dimensional model of our own Galaxy was constructed.

With the extension of observations to shorter wavelengths, five other emission processes became observable, namely (1) the *free-free emission* from thermal electrons in ionised regions around hot young stars, (2) the *recombination lines* that are emitted when ionised hydrogen atoms capture free electrons and become neutral, (3) the *cosmic microwave background radiation* as a relic from the 'big bang', (4) the *rotational lines* from a multitude of molecules that exist in space, in particular in star forming regions, but more generally in 'cold' parts of the Universe where the temperature is only tens to a few hundred degrees above absolute zero. This is the temperature range in which (5) *cold dust particles emit strongly by re-radiating energy* originally produced at much shorter wavelengths of the optical and ultraviolet domain, but which is strongly absorbed by the dust.

These examples suffice to explain why radio astronomy has made many impressive discoveries since its beginning more than 50 years ago and why much effort has been spent by scientists, engineers and technicians to build ever more powerful telescopes, and more sensitive receivers and spectral backends that allow to analyse cosmic radio signals in great detail. With projects like the Atacama Large Millimeter Array (ALMA) the field will see another giant step forward at the shortest wavelengths accessible from the ground, and with the Square Kilometer Array (SKA) that is currently in its conceptual design phase another step forward will be made at the long wavelength end of the radio window.

The present book is about radio telescopes, and more specifically about their thermal design and behaviour and that of their enclosures where it applies. In addition to gravity that influences the shape and possible deformations of large mechanical structures, the response to environmental influences determines the quality of a radio telescope. Among these, thermal influences caused by varying solar irradiation, by day-to-night temperature changes and by seasonal variations are the most severe factors, together with strong and time-variable wind loads, that can occur.

The authors belong to the small group of scientific experts who have focused on the theoretical and practical treatment of thermal influences on modern radio telescopes and their enclosures. They have developed and applied techniques that allow to model a telescope structure with all its major components under the influence of realistic environmental conditions. From these computer models they are able to predict the response of a telescope to changing environmental conditions. This helps to check in advance whether a given design concept will meet the specifications within the tolerances that allow to carry out the observations for which a telescope is built.

The authors' approach is unique by combining theoretical and modelling concepts with a large collection of relevant telescope data, in particular a large amount of temperature measurements from existing telescopes. A full chapter is devoted to the measured thermal behaviour of radio telescopes and the authors illustrate in very practical terms how much the modelling helps to predict the actual thermal behaviour both at component and at system level and how far model calculations can help to understand the observed phenomena. The detailed discussion is based on a unique database that the authors have been able to compile because of their involvement in many different projects. Such information is usually very difficult to find because it tends to be hidden in internal technical reports, produced either in institutes or in industry.

The insight that the reader can gain from this comprehensive approach to the thermal design and thermal behaviour of radio telescopes will benefit the scientist and the engineer, both in academia and in industry, who think about the next generation facilities. At the beginning there must always be a set of clearly defined scientific goals that cannot be reached with any of the existing facilities, and that are considered to be of fundamental importance both by the scientific community and by the potential funding agencies. The top priority science goals can be translated into a set of scientific requirements (e.g. wavelength range to be covered, sensitivity limit to be reached, angular resolution to be achieved etc.) which in turn are translated into technical specifications for which the new facility must be designed. These critical performance criteria ultimately determine the design concepts, the choice of materials, the location where the new facility will be operated etc. and, last but not least, the total cost. The better the interdependence between these parameters is understood – and thermal behaviour is among these aspects – the more realistic can a new facility be planned, costed and built.

In addition, the insight that the reader can gain from this study of thermal design and behaviour of radio telescopes will benefit scientists and operators of existing facilities. Many, if not all, of the radio telescopes that are currently in operation underwent significant improvements beyond their original specifications during the years that followed their commissioning. This is due to a long-term monitoring of the mechanical performance and the reactions to the actual environmental conditions, and a better understanding of the reasons for change. In many places this is a continuous effort that is, of course, not limited to the telescope but includes other components like receivers and backends as well.

The methods described in this book and illustrated with specific examples, and the thermal data that have been collected, are primarily orientated towards radio telescopes. They are, however, also of interest for the design and construction of deep space communication antennas, and even for the design and construction of current generation large and next generation extremely large optical telescopes and their enclosures. Scientists and engineers involved in these projects will, in my view, also benefit from the material that the authors have collected and well documented in this book.

Michael Grewing
St.Martin d'Hères, March 2009

Preface

The success of radio astronomy – especially microwave radio astronomy – and the possibility of communicating with spacecrafts far away in the planetary system is among others due to the construction of radio telescopes and antennas[1] with good beam quality and pointing stability. The design and construction of telescopes has to consider and to suppress, as far as possible, the degrading effect of gravity, temperature and wind. Gravity is a quasi–static force that can be handled exactly in finite element calculations and considered correctly in the construction and operation of a telescope. The influence of gravity does usually not involve a loss in observing time, although perhaps causing some unavoidable degradation of telescope performance as for instance experienced in the gain elevation dependence of a radio telescope. Through contact with the thermal environment a telescope is influenced by temperature changes that may result in thermal deformations of the structural components. Thermal deformations can be calculated with good precision and sometimes compensated in the case the instantaneous temperature distribution throughout the telescope structure is known from measurements or calculations. However, in practice this is usually not the case and direct measures of thermal control are taken through application of white paint, insulation and in some cases ventilation and climatisation. This may help to a large extent although a full thermal control is seldom achieved, especially for open–air telescopes. In several cases this has led to radome or astrodome enclosed radio telescopes. There seems to occur, generally, some loss in observing time due to a telescope's uncontrolled thermal behaviour. An open–air telescope (or even a ventilated telescope in a radome) is in addition exposed to wind forces. While the effect of simulated wind loads can be predicted with good success from finite element calculations, a real time control of wind influences has hardly been tried. Dependent on the characteristics of the observatory site, the loss in observing time due to wind can therefore be high. Finally, the influences of gravity, temperature and wind must be compared to the variability of the atmosphere that is

[1] Astronomy uses the term radio telescope, communication technology the term antenna. The construction of radio telescopes and communication antennas is similar. From our background and the presented examples we speak about radio telescopes, without preference for one or the other term.

today beyond active control in single–dish radio observations. The table summarizes these effects.

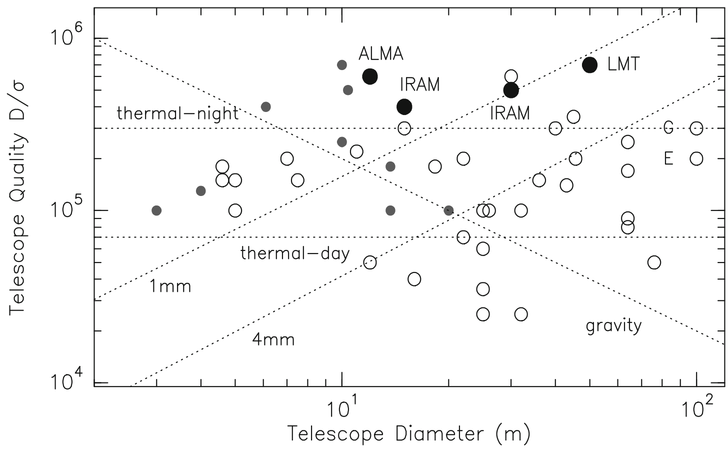
Forces acting on a Telescope (and Enclosure).

Influence/ Force	Time Variability	Components	Loss of Observing Time
Gravity	quasi–static	gravity	negligible
Temperature	slow 1/4 – 3 h	air, wind, sun, sky, ground & internal heat source	some
Wind & **Gusts**	fast, 1/10 – 10 s	ambient air	important
Atmosphere	fast	temperature, H_2O vapour, clouds, precipitation	(dominant)

A large variety of telescope constructions exists, ranging from the earlier long–wavelength dipole and meshwire telescopes to modern high precision reflector telescopes for centimetre, millimetre and sub–millimetre wavelength observations. The desired performance of a radio telescope is calculated from electromagnetic diffraction theory, the actual performance of a radio telescope under gravity, temperature and wind is a matter of design and construction, based on experience and calculations. Central in the study of the thermal behaviour of a telescope, and of the protecting enclosure, is the question of the temperature of telescope components, as a function of time, and of the associated structural deformations. Temperature induced deformations of the telescope may lead to a transient performance degradation with a focus and pointing error and a decrease in sensitivity.

The text deals with full aperture reflector radio telescopes and antennas, of which examples are shown in Chapter 1. Full aperture telescopes for observations at centimetre, millimetre and sub–millimetre wavelengths (λ) require a reflector surface precision of $\sigma \lesssim \lambda/16$ (root mean square value), i.e. of approximately 0.02 to 1 mm, and a focus and pointing stability of $\sim \lambda/10$ and $\sim 1/10$ of the beam width, i.e. between approximately 10 to 1 arcsecond. A connected radio interferometer, which consists of several telescopes observing together, needs in addition a phase stability and hence a mechanical stability of a few $\lambda/10$, at least in between calibrations. By taking proper considerations in the design, these fundamental specifications must be realized in the integrated telescope structure. Von Hoerner [1967 a, 1977 a] estimated the limitations in reflector diameter (D) and reflector quality (D/σ) when affected by elastic deformations due to gravity, temperature and wind. A summary of centimetre– and mm–wavelength telescopes with respect to structural limitations of stress (mass) and temperature induced deformations is shown in the von Hoerner–diagram. With respect to the behaviour of short wavelength radio telescopes, the situation displayed here illustrates the necessity to reduce the influence of the ambient thermal environment.

Ideally, a radio telescope should maintain a uniform temperature in the variable ambient thermal environment. However, depending on the affordable technical



Von Hoerner–diagram. Telescope quality D/σ (D = reflector diameter, σ = surface precision, rms value) and natural limits of gravity and thermal effects, for mm – wavelength (•) and cm–wavelength telescopes (○). The lines labelled 1 mm and 4 mm show the relation $\lambda_{\min} = 16\,\sigma$. For the limiting relations see von Hoerner [1967 a, 1977 a] and Baars [2007]. G = GBT telescope, E = Effelsberg telescope.

efforts and costs, this condition can be realized only within certain limits. Tolerable departures from temperature uniformity, expressed for instance as the root–mean–square value (rms) of temperature fluctuations or tolerable thermal gradients across the telescope structure, can be estimated from structural finite element calculations. Such calculations and the known thermal behaviour of existing telescopes define the necessity and the design parameters of a thermal control system. The thermal uniformity and structural stability of a telescope may need to be realized by either *passive* thermal control consisting of a choice of materials, paint and insulation or in addition *active* thermal control employing ventilation and/or climatisation (with heated or cooled ventilating air). Some mm–wavelength radio telescopes, in particular those of the earlier generation built from aluminium, are protected by a radome (or astrodome) with a stable internal thermal environment.

The text contains four main topics, i.e. the Basics of Heat Transfer, Thermal Model Calculations, the Thermal Environment and a Collection of Temperature Measurements of telescope structures. It summarizes the progress in thermal engineering and thermal calculations, including the testing phase of the ALMA prototype telescopes in 2005, and is meant to be a sketch of the established *state of the art* at the time of its publication. The design of other large telescope projects is not yet reported in detail.

Heat Transfer Relations. The thermal state of a telescope is determined by heat transfer between its components, the enclosure and the environment. Heat transfer occurs by conduction, convection and radiation. The relevant physical relations are explained in many textbooks, either on the basis of fundamental physics or engineering purposes. With the exception of relatively simple structures of plates and tubes that can be treated in analytic form for the fundamental processes, the application of the basic relations to large and complex structures like telescopes and enclosures can become very difficult and not treatable in analytic form because of the many interconnected components, complicated geometrical shapes, natural and forced air flow and complex radiation fields. The text explains the modes of heat transfer as necessary for the understanding and modelling of the thermal behaviour of telescopes and their enclosures. This includes, for instance, heat transfer through plates and honeycomb structures as used for reflector panels and walls of enclosures; relations of convective and radiative heat transfer in tube and plate networks as used in reflector backup structures; ventilation and climatisation systems of backup structures, quadripods, focus cabins and fork supports. These relations include the connection of the telescope and enclosure to the time variable thermal environment with wind induced convection, radiative connection of the telescope and enclosure to the cool sky and the warm ground, and the influence of solar radiation.

Thermal Model Calculations. Thermal model calculations can today be made with good precision, allowing detailed exploratory numerical studies. A significant part of a thermal study occurs during the design of a telescope and enclosure. At that time thermal model calculations are made with the intention of deriving representative temperatures of the telescope and enclosure components. From these calculations a prediction can be made of temperature induced structural deformations and compared with the performance specifications. If necessary, in these model calculations passive/active thermal control is studied and modified until the performance criteria are fulfilled. This may lead to the design of insulation and ventilation systems.
Several thermal models are explained in the text. The models refer to structures of increasing complexity, i.e. of increasing mass and increasing surface area, thus requiring an increasing number of thermal nodes.

The Thermal Environment. A telescope interacts with the local thermal environment, unless the influence of the environment is reduced or nearly eliminated by an enclosure, a radome or an astrodome. Each local environment has its own characteristics that can be taken from meteorological data or must be determined from site tests. The characteristics of the environment are taken into account in the design and operation of a telescope and its enclosure. From the large variety of local conditions a selection is made in the text of a low altitude, grassland and forested site (Effelsberg, Germany), of a mountain site (Plateau de Bure, France, and Pico Veleta, Spain) and of a high altitude desert mountain site (Chajnantor, Chile). From the meteorological data several statistical parameters can be derived that define the thermal specifications for design and operation of a telescope and enclosure, either under normal operation conditions or extreme conditions of survival.

Temperature Measurements and Data Sources. Before starting a thermal design, it is helpful to have some knowledge of the actual thermal behaviour of existing telescopes and enclosures and of the thermal environment in which the telescopes operate. Observatory reports containing a large amount of data are occasionally published, some information is found on the internet. The reports provide valuable guidelines for the design, installation, operation and improvement of thermal equipment, but also recordings of temperatures of telescopes that can be used as basic test data for model calculations of telescope structures. Another source of information exists with the construction firms. This information is often not available and sometimes classified because of proprietary rights. The text collects representative data, as far as accessible, on thermal conditions at observatory sites and on the thermal behaviour of existing telescopes and their enclosures. The collected data are necessarily incomplete and may provide only a limited view of a telescope's thermal behaviour.

Although the text concentrates on radio telescopes for astronomical research, the design and construction and hence the thermal behaviour of Communication and Deep Space antennas is rather similar. Communication and Deep Space antennas can be open–air antennas or radome enclosed antennas. The main difference is the longer wavelength of operation compared to millimetre and sub–mm telescopes and a comparably lower required structural precision and stability.

Literature

The theory of heat transfer, either from the perspective of fundamental physics or engineering application, is published in many textbooks. There are several publications on the measured thermal behaviour of telescope structures and on corresponding model calculations of their static or time–dependent dynamic thermal behaviour. The publications are scattered throughout many journals and often inaccessible observatory reports; the major accessible publications are mentioned. To our knowledge, the only textbook on *Climatic Influences on Antenna Systems* was published by Bairamov et al. [1988, in Russian]; an English translation is not available. A summary of environmental effects on optical telescopes and enclosures was published by Wilson [1999] in *Reflecting Telescope Optics II*.

Albert Greve and Michael Bremer
July 2009

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The participation in Thermal Aspects of several Telescope Projects provided an overview of current telescope contructions, thermal specifications and engineering solutions, i.e. of the IRAM telescopes at Pico Veleta (Spain) and Plateau de Bure (France), the Heinrich Hertz Telescope at Mount Graham (USA), the Large Millimeter Telescope at Mount Sierra Negra (Mexico, USA), the Sardinia Telescope (Italy), the ALMA AEC prototype telescope (EIE, Italy, and ESO, Germany), the ESA 35–m antenna at Perth (Vertex Antenna Technik, Germany) and the solar telescope project THEMIS (France).

Several Data are taken from Observatory Reports, mostly available on the observatory web–sites. We especially mention the reports by S. von Hoerner (NRAO archive), J. Lamb (Caltech, USA) on the BIMA and OVRO telescopes, the reports by N. Ukita and N. Satou on the NRO telescopes (Japan) and the web–site data of the JCMT telescope. *Astronomy and Astrophysics*, *Radio Science*, *Journal of Infrared and Millimeter Waves*, *IEEE Transactions on Antennas and Propagation*, *IEEE Antennas and Propagation Magazine*, *Infrared Physics* and *SPIE Conference Publications* gave permission to use some of their published figures and tables. We are pleased with the permission from NRAO, MPIfR, CSO and GMRT to publish pictures of their radio telescopes and the CSO astrodome.

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Contents

Acronyms

AZ	Azimuth
BB	Black Body (radiation)
BUS	Backup Structure
CFRP	Carbon Fiber Reinforced Plastic
CTE	Coefficient of Thermal Expansion
DOF	Degrees Of Freedom
EL	Elevation
FBA	Flexible Body Analysis
FEA	Finite Element Analysis
FEM	Finite Element Model
FWHP	Full Width Half Power
HC	Honeycomb (panel)
TM	Trademark
VLBI	Very Long Baseline Interferometry

Telescopes, Observatories, Organizations.

Abbreviation		Country
Radio Telescope		
ALMA	Atacama Large Millimeter Array	Chile
APEX	Atacama Pathfinder Experiment	Chile
ASTE	Atacama Submillimeter Telescope Experiment	Chile
BIMA	Berkeley–Illinois–Maryland Association Millimeter Array	USA
CARMA	Combined Array for Research in Millimeter–Wave Astronomy	USA
CCAT	Cornell Caltech Atacama Telescope	Chile
CSO	Caltech Sub–Millimeter Observatory	Hawaii
Effelsberg	Max Planck Insitute for Radioastronomy	Germany
FCRAO	Five College Radio Astronomy Observatory	USA
GBT	Green Bank Telescope	USA
GMRT	Giant Metre–Wave Telescope	India
HHT (SMT)	Heinrich Hertz Telescope	USA
JCMT	James Clerk Maxwell Telescope	Hawaii
Kitt Peak	National Radio Astronomy Observatory	USA
LMT/GTM	Large Millimeter Telescope/ Gran Telescopio Millimetrico	Mexico
LOFAR	Low Frequency Array	The Nether–lands, Germany
MERLIN	Multi–Element Radio Linked Interferometer Network	England
NMA	Nobeyama Millimeter Array	Japan
NOTO	NOTO Radio–Astronomy Observatory	Italy (Sicily)
OVRO	Owens Valley Radio Observatory	USA
PV	Pico Veleta IRAM 30-m Radio Telescope	Spain
PdB	Plateau de Bure IRAM Interferometer	France
RT-70	Russian 70-m Radio Telescope	Russia
SEST	Swedish ESO Sub–Millimeter Telescope	Chile
SKA	Square Kilometre Array	
SMA	Sub–Millimeter Array	Hawaii
SRT	Sardinia Radio Telescope	Italy
VLBA	Very Long Baseline Array	USA
VLA	Very Large Array	USA
Optical Telescope		
CFHT	Canada France Hawaii Telescope	Hawaii
ELT	Extremely Large Telescope	ESO–Germany
MMT	Multi–Mirror Telescope	USA
NTT	New Technology Telescope	Chile
VLT	Very Large Telescope	Chile
Organisations		
ESO	European Southern Observatory	Germany/Chile
IRAM	Institut de Radioastronomie Millimétrique	France/Spain
JPL	Jet Propulsion Laboratory	USA
MIT	Massachusetts Institute of Technology	USA
MPIfR	Max Planck Institute for Radioastronomy	Germany
NRO	National Radio Observatory	Japan
NRAO	National Radio Astronomy Observatory	USA