DESIGN PHILOSOPHY AND TECHNOLOGY ASPECTS OF SUBMILLIMETER WAVELENGTH RADIO TELESCOPES

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ABSTRACT

Telescopes for wavelengths between 0.3 and 1 mm need a reflector surface accuracy of better than 25 m and a pointing precision of <1" under operational conditions. It is essential to control gravitational and thermal deformations to very small values. These can be achieved by the use of carbon fiber reinforced plastic materials and multi-parameter structural optimization. This is illustrated by the design of the 10-m Submillimeter Telescope (SMT) of the MPIfR and Steward Observatory. We also discuss shortly the characteristics of present day receivers for these wavelengths. SIS-diode technology can now be applied to frequencies of about 500 GHz.

1. The rationale for a Submillimeter Telescope

1. 1. astronomical.

Since several years it is clear from developments both in the millimeter and the infrared range of the spectrum, that decisive information can be obtained from observations in the last remaining window at wavelengths between 100 m and 1 mm.

Here the radiation of cold dust reaches its highest intensity. Apart from the study of interstellar, and probably protostellar, condensations, new prospects arise for the observation of active galaxies and quasars, especially if the angular resolution can be increased. It is likely that submillimeter observations, in combination with IRAS data, will enable us to make some definitive decisions on the nature of the origin of the strong continuum radiation in extragalactic objects.

Also the higher rotational transitions of the polyatomic molecules fall in this region, enabling one to probe the warmer and denser parts of the interstellar and circumstellar clouds. The spectral lines of hydrides and several atomic transitions are found here; all these are important for the cooling of the interstellar medium.

Work with the millimeter telescopes in Japan and Spain, as well as millimeter interferometers, have-shown the importance of a high angular resolution of the order of 10 arcseconds or better. Consequently a similar resolution at submillimeter wavelenghts is highly desirable, requiring a telescope with a diameter of the order of 10 m. Clearly this can only be exploited if detector systems of sufficient sensitivity are available.

1.2. technical

The completion of several large millimeter telescopes, notably the 30 m IRAM telescope on Pico Veleta, pointed the way to even more accurate telescopes for the submillimeter range. The first telescopes, which are capable of observing in at least the longer wavelength windows of the submillimeter region are now in use: the JCMT, CSO, and SEST instruments with diameters of 10-15 m have reached reflector accuracies of 30-60 m, allowing observations to a highest frequency of about 600 GHz.

In the 15-m telescopes for the IRAM interferometer extensive use is made for the first time of carbon fiber reinforced plastic (CFRP) for the reflector support and panel structures. In a next step, the Max-Planck Institut für Radioastronomie (MPIfR), in cooperation with the companies Krupp, Dornier and MAN started the design project for a 10 m telescope, which should perform nearly perfectly at the shortest wavelength, where the earth's atmosphere is at least partially transparent under favourable conditions. This means that we aimed at a reflector inaccuracy of not more than 15 m (< /20 at 350 m). At this wavelength the beamwidth of a 10 m telescope is less than 10 arcseconds. Thus we require a pointing and tracking accuracy of better than 1 arcsecond under all operational conditions! The most critical aspects of the design are the fabrication of the reflector panels and the minimization of deformations caused by temperature differences in the support structure.

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2. Obstacles towards submm observations

2.1. the atmosphere

A number of transitions of oxygen and water vapor lie in the mm- and submm-region of the electromagnetic spectrum. These cause a strong absorption in the terrestrial atmosphere, leading to a limited number of "windows", through which the sky can be observed from the ground. Since the density of water vapor decreases rather fast with height (the scale height is about 2 km), the quality of the observing site improves with increasing altitude. For frequencies above 300 GHz the situation requires a site with a clear sky and the lowest possible water vapor concentration. In the two windows near 350 and 450 m even a precipitable water vapor column of only 1 mm leads to a zenith transmission of about 0.4. Thus submillimeter telescopes are located at elevations in excess of 3000 m, causing special problems regarding the operation and survival.

2.2. receiver technology

Apart from the planets, no objects are strong emitters in the submillimeter range and the signals are very weak. Moreover the development of receivers for these wavelengths is state of the art and not comparable with the situation at cm or mm wavelengths. This is particularly true for coherent detectors, where even the best Schottky diodes at present give receiver temperatures of several thousands Kelvin at 350 m wavelength. Broadband continuum observations fare better with the high sensitivity bolometers, cooled to 0.3 K or even lower.

Several laboratories are pushing the limits of SIS-diodes to higher frequencies and SIS-systems at 490 GHz are now operational. Efforts are under way at several institutes to reach frequencies near 1 THz with Niobium-Nitrite-type SIS-diodes.

2.3. antenna technology

As noted above a submillimeter telescope must have a surface accuracy of less than 25 m and a pointing accuracy of better than 1". This puts high demands on the technology of reflector antennas and their associated drive systems. While the application of homology methods in the structural design can limit the gravitational deformations to very small values, the control of thermally induced deformations is much more difficult, albeit absolutely necessary for our requirements. For instance a temperature change of 1 K in an aluminium beam of 4 m length causes an expansion of 100 m! Such deformations not only deform the reflector well beyond an acceptable level, they also cause severe pointing errors.
In Fig.1 we show the position of a number of radio telescopes on a diameter versus accuracy plot. The lines indicate natural boundaries, based on material characteristics. All telescopes above the "gravitation" line are of an advanced, homologous design. Most accurate ones are limited by thermal effects, unless special precautions (CFRP material or effective insulation) are taken.

3. The 10-m Submillimeter Telescope (SMT)

We now describe the major aspects of the design of the SMT in order to illustrate the present state of the art in high-accuracy reflector antennas. As we noted above, a key feature of the SMT is the extensive application of CFRP in the backup structure and the surface panels of the reflector. The most attractive feature of this material for our purpose is the extremely small coefficient of thermal expansion (about 10^{-6}). It appeared feasile to maintain the strict tolerances on the allowable deformations in operation under full influence of sunshine. Thus our design considered from the outset a reflector support structure and reflector panels of CFRP. Krupp Industrietechnik designed and fabricated the mount and backup structure, while M.A.N. Technologie was responsible for the panels and the subreflector.

3.1. major design characteristics of the SMT

3.1.1. the mount

The mount is a elevation over azimuth mount, made of steel and thermally insulated by a layer of polyurethane foam. Because the CFRP reflector structure is relatively light, special attention has been given to the design of the servo-drive system. The transmission ratio between drive motor and telescope axis is about 5000. The drive motors are d.c.-disk motors with a low moment of inertia. Angle encoders on both the telescope and the motor axes, together with additional accelerometers provide the input signals to a state controller, which should provide positioning and tracking to within 1 arcsecond in operational winds of 12 m/s. The top plate of the elevation section with 3.5 m diameter forms a support with uniform stiffness for the CFRP reflector structure.

3.1.2 reflector support structure

This support is a standard space frame structure, made of CFRP tubes connected to invar steel nodes. Fig. 2 presents a picture of the preassembled structure. A large effort was spent by the team at Krupp on the optimization of this structure for several parameters simultaneously. Thus a design was sought in which maximum stiffness and minimum weight were obtained, while minimizing the effects of humidity (CFRP is hygroscopic) and of temperature changes. Extensive theoretical and experimental studies were made to accurately characterize the CFRP material. An example is shown in Fig. 3 for the temperature and humidity effects on a CFRP tube. The structure shows excellent tolerance parameters, as shown in the Table. Several experiments were performed on the assembled structure. The deformation under static loads was measured and compared to the theoretical calculations (Fig. 4). Also a number of eigenfrequencies was measured under dynamical loading conditions, yielding values within a few percent from the calculated ones. This demonstrates the high accuracy of the calculations and is of great value for the implementation of the servo algorithms. The results increase our confidence in the calculated performance of the telescope (Mäder et al., 1990).

3.1.3. reflector panels

The reflector surface is subdivided in three concentric rings of 12, 24 and 24 trapezoidal panels, respectively. For the panels it is also essential to minimize the thermal deformations. Thus they are made of a composite structure consisting of a 90 mm thick flexible aluminium honeycomb core, to which CFRP sheets of 1.2 mm thickness have been bonded. The coefficient of thermal expansion of the panels is approximately 3.10^{-6}. The paraboloidal contour of the panels is achieved by replication on a mold of pyrex glass, produced by the Optical Sciences Center of the University of Arizona. These molds were figured with a new large optical grinder to an accuracy of 3 m rms (Baars and Martin, 1986).

The panels are relatively large, having a diagonal of about 2 m. To reach the required accuracy, the manufacturer, M.A.N. Technologie, has developed a two stage process. A "rough" panel is fabricated first, a procedure which involves curing of the composite at high temperature. Upon cooling after the curing, some generally large-scale deformation is unavoidable. This is corrected by a final step in which the reflecting skin (a 40 m thick aluminium foil) is laid out on the mold and bonded to the panel. The hardening of the epoxy is now done at room temperature and no deformations are introduced. The average contour accuracy of the panels is 7 m.

3.1.4. measurement and setting of the panels

The achieved high accuracy of the reflector and the panels, each better than 10 m under all operational conditions, can only be exploited, if the panels are set to the desired reflector contour with a similar accuracy. This imposes a formidable measuring task. For the SMT we plan a three-step approach. The first will be a standard, but carefully executed, theodolite-tape measurement, which will deliver a surface accuracy of about 50 m. This will be followed by a radio-holographic method, using the LES 8 satellite at 37 GHz as a source. Based on experiences on other telescopes, we should reach 25 m overall accuracy. This will make the telescope useable in the window near 700 GHz. Finally we plan to exploit the high reflecting quality of the panels to use an interferometer at 10 m wavelength to measure the small scale errors with an accuracy of better than 10 m.

It is worthwhile to note that the development of high accuracy antenna structures with CFRP opens exciting possibilities for submillimeter telescopes in space. Both the extremely small coefficient of thermal expansion and the relatively low weight (about 5 times less than steel for a comparable stiffnes) render this material very suited for space applications.
For more details on the SMT project, see Martin and Baars (1990).

4. The receiver-instrumentation for the SMT

The first receivers for the SMT will be cooled SIS-Diode mixers for the 350 and 460 GHz windows along with a number of Acousto-optical Spectrometers with several bandwidths and resolutions. For broadband continuum observations a ^{3}He-cooled germanium bolometer, equipped with several filters for the submillimeter windows will be provided. These instruments are already in use or under construction. Work has also started on a waveguide SIS-mixer for the 700 GHz window and on an "open structure corner cube" Schottky-Diode mixer receiver for the 800 GHz band. Further development for SIS-systems is underway with an aim of achieving 1 THz. Also development of a multichannel array of bolometers is in an advanced state.

The development of these receivers is a necessity for any observatory, because they are not commercially available. The state of the art in thias field indeed is to be found at a small number of radio observatories. The required technologies range from submicron size devices, as SIS- and Schottky-diodes, via quasi-optical techniques for wavefield transformation to cryogenic techniques at temperatures below 4 kelvin. At the present time receiver noise temperature of about 10 times the quantum limit has been achieved with SIS-mixers at frequencies around 100 GHz. In the submillimeter range, the difference is still quite larger, but good advances are being made for frequencies up to 500 GHz.

Acknowledgement is due to the design teams at Krupp and M.A.N. for their excellent achievements in the design and construction of the SMT.

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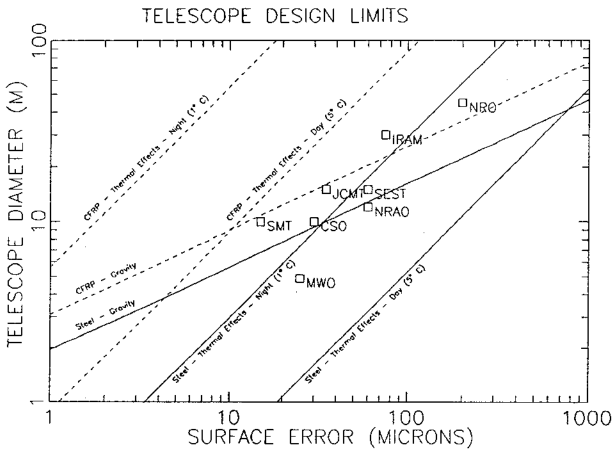


Fig.1. "Natural limits" due to gravitational and thermal effects and a number of (sub-)millimeter telescopes in a diameter vs. surface error plot.

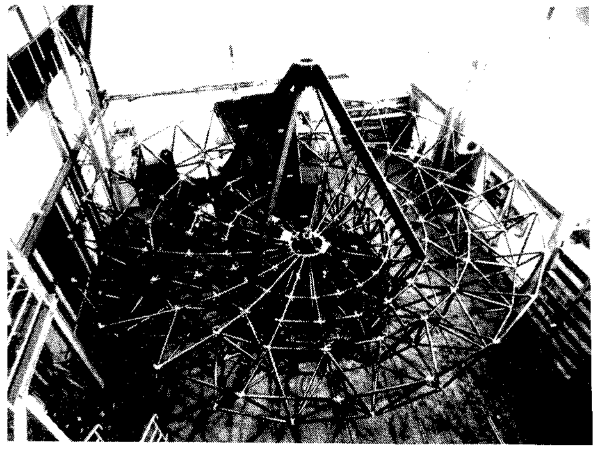
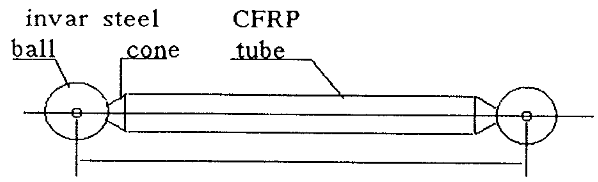


Fig.2. The assembled CFRP space frame reflector support of the SMT with the CFRP quadrupod and a number of test panels installed.



measuring length = 522 mm
tube diameter = 50 mm

PARAMETER	COMP.	MEAS.
compliance (μm/kN)	10.75	10.76
thermal coefficient (10^{-6}/K)	0.62	0.65
hygroscopic coeff. (10^{-6}/%)	121	120

Fig.3. Comparison between computed and measured parameters of a CFRP member with invar joint.

SMT STRUCTURAL PARAMETERS

GEOMETRY

PARABOLIC MAIN REFLECTOR	- diam (m)	10
HYPERBOLIC SUBREFLECTOR	- diam (m)	0.69
PRIMARY REFLECTOR	- f/D ratio	0.35
CASSEGRAIN/NASMYTH	- f-number	13.8

TOLERANCES OF REFLECTOR SUPPORT STRUCTURE

LOAD CONDITIONS	RMS DEFORMATION(m)
Gravity - Horizon	5.2 (2.8)*
Gravity - Zenith	3.1 (2.8)*
Temperature - ambient change 20 K	3.2
- gradient top/bottom 6 K	0.6
- gradient front/back 4 K	0.6
- gradient in time 5 K/h	2.9
Wind 12 m/s - Horizon	2.0
- Elev. 50°	5.4
- Zenith	4.0
Seasonal humidity variation	<3.0**
TOTAL (rss) - at elev. 60°	6.9 m

* - assuming panel setting at 45° elevation
** - with preconditioning of CFRP parts

SUMMARY OF OVERALL CHARATERISTICS

Deformation of support structure	7
Fabrication of panels	7
Deformation of panels under loading	5
Measuring/setting of reflector	10
Total overall surface error (rss)	15 m

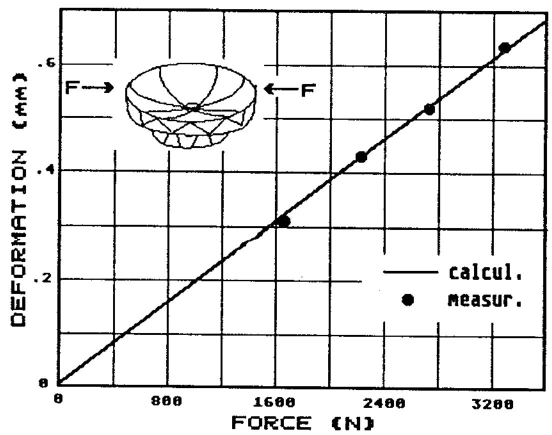


Fig.4. Comparison between computed and measured deformation of the space frame under static loads.