Research on High Precision Antenna For DATE5

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Abstract—**Dome A 5m Terahertz Explorer(DATE5) is a proposed telescope to be deployed at Dome A, Antarctica to explore the excellent terahertz observation condition unique to the site. The telescope needs to realize and maintain an overall reflector surface accuracy of 10μm rms and a blind pointing accuracy of 2 arcseconds under the extreme site conditions and unmanned operating mode. Two candidate antenna designs have been proposed, one of which is based on an all-CFRP reflector and slant-axis mount and the other based onaluminum panels on carbon fiber backup structures and altazimuth mount. Both aluminum and CFRP sandwich prototype panels have been fabricated and tested in a climate chamber. The aluminum panel shows desired surface accuracy from room temperature down to -60°C. CFRP panels with different sandwich structures are fabricated and tested. All of them achieve a surface accuracy around 5μm rms at room temperature, but their surface accuracy differs significantly when they are cooled, indicating the importance of panel structural design. The aluminum and CFRP panels are equipped with different type of de-icing heaters, and their performances have been verified respectively. Structural and thermal analyses on the overall antenna shows that both of the two candidate designsmeet the specifications of DATE5. Moreover, demonstration experiments on near-field radio holography are performed and a repeatibility accuracy of 3μm rms is achieved.**

INTRODUCTION

Dome A 5m Terahertz Explorer (DATE5) is a proposed telescope to be deployed at Dome A, Antarctica to explore the excellent terahertz observation condition unique to the site [1]. One of the key challenges of the telescope is to realize and maintain the required 10micronsrms overall reflector surface accuracy under the extreme site conditions at Dome A[2].To realize this objective, some key technologies of the telescope need to be studiedincluding prototyping of reflector panels and corresponding environmental experiments, de-icing techniques, and surface profile measurement technology, etc. In the preliminary design phase of DATE5, two candidate designs for the main reflector were proposed. Thefirst design is based on aluminum panels on carbon fiber reinforced polymer (CFRP) backup structures.In the second design, panels are made ofsandwich structures with CFRP front and back skins and an aluminum honeycomb core, and the backup structures are made of CFRP truss. According to the surface error budget for DATE5, the manufacturing error of each reflector panel should not exceed 5 microns rms, and the gravitational and thermal deformations of the panels should be kept on the level of a few microns rms, which is very challenging considering the extreme site conditions at Dome A.

Prototyping of both aluminium and CFRP panels have been carried out to verify the corresponding manufacture technologies.The aluminumprototype panel (0.4m × 0.6m in size) was directly milling machined. Several CFRPprototype panels (1m× 0.6m in size) were fabricated on the same high-precision invar mould. The figuresof two types of panels wereboth measured on a three coordinate measurement machine (CMM).The measured surface errors are 3.2 and 5.1 microns rms at the room temperaturefor the aluminium and CFRP panels respectively. However, the thermal deformationof the two types of panelsdue to the large seasonal soak temperature variationis still not clear. To verify the performance of the panel under extreme cold environment, the surface figures of both prototype panelsweremeasured in a climate chamber whose interior temperature was varied from room temperature down to -60°C.

Reflector panels working at Dome A run high risks of icing[3], and active de-icing mechanisms has to be implemented on the panels. Aluminum and CFRP panels are equipped with different types of de-icing heaters, and their respective performances needs to beverified experimentally.

DATE5 will employnear-field radio holography to align the reflector panels. In order to eventuallyrealize anoverall surface accuracy of 10μm rms, the repeatability error of the holographic measurements should be less than 3μm rms.To evaluate the feasibility of near-field holography for DATE5, a dual-channel radio holography receiver operating at the 3-mm waveband were developed[4]. Demonstration experiments on a 1.45m test antenna were performed and the results were reported and analysed at the end of this paper.

PROTOTYPING FOR ALUMINUM PANEL

The prototype for the aluminum panel is a 400×600mm fan-shaped panel with back stiffening ribs. The panel is directly milling machined out of aluminum alloy (LC4) on a high speed machining centeras a single piece. After the fabrication process, the surface figure of the panel was first measured on a CMM. The measured surface is best fitted with a parabolic surface with a focal length slightly larger than 2000 mm and the residual error is 3.2 μm rms. The front and back view of the panel is shown in Fig. 1.

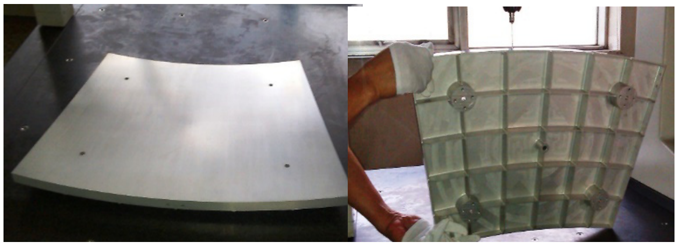


Fig. 1Prototype aluminium panels for DATE5

A. Surface Figure at Low Temperatures

Since the CMM cannot operate in a climate chamber under low temperatures, we measure the panel surface using photogrammetry. The measurement setup is shown in Fig.2.

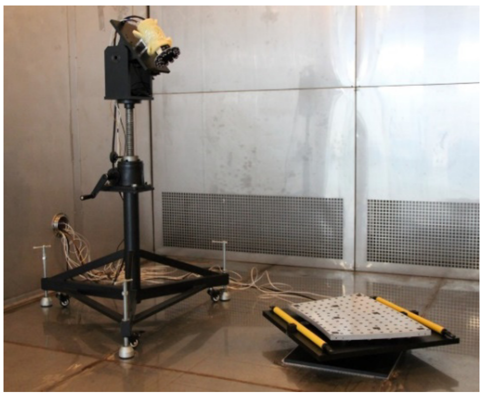


Fig. 2Experimental setup of the photogrammetry measurement in a climate chamber.

The photogrammetry measurement system demonstrated a repeatability error of 1.3, 1.4 and 1.0 microns rms in the x, y and z direction respectively at room temperature in the laboratory. However, when operating in the climate chamber at low temperatures the repeatability errors degrades to 3.6, 3.5 and 2.1 microns rms in the x, y and z direction respectively. The degradation is mainly due to the mechanical vibration and air turbulence in the climate chamber.

Panel surface figures are measured at several typical ambient temperatures from 25°C to -60°C.The measured surface rms errors before and after removing the defocusing component is listed in Table I for various ambient temperatures. It can be seen from TableI that at the lower temperatures the surface error increases only slightly after removing the defocusing component, indicating that the major contributors to the surface errors are the manufacture error and a defocusing error. No additional surface error caused by internal stress is observed under temperatures down to -60°C.

TABLE I RMS SURFACE ERROR UNDER VARIOUS AMBIENT TEMPERATURES FOR ALUMINUM PANEL (UNIT: MICRON).

Ambient Temperature	T=26°C	T=0°C	T=20°C	T=-40°C	T=-55°C
Fixed-focus Fitting (f=2000mm)	3.2	3.6	3.6	3.9	4.6
Best fitting	3.0	3.6	3.5	3.6	3.8

B. Panel De-icing

The anti-icing system implemented on the aluminum prototype panel composes of a 30 identical heater pads and a feeding network. The heaters are polyimide film heaters tailored into square pads fitting into the pockets of the panel back, as shown in Fig. 3. Such type of films is suitable to work at temperatures as low as -100°C.

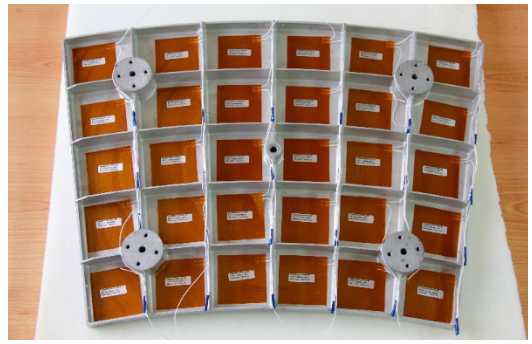


Fig. 3Aluminum panel anti-icing system.

First, we test the performance of the panel anti-icing system at room temperature in the laboratory. An input heat flux of 60W/m^2 is applied to the panel and the back and side of the panel are thermally insulated to simulate the situation on the real telescope. The temperature distribution of the panel front surface obtained by an infrared camera is shown in Fig.4. The average temperature increase is measured to be 3.0°C and the peak-to-valley temperature difference across the panel is less than 0.5°C. Similar results are found at low temperatures in a climate chamber. In such cases, panel temperatures are measured by RTD sensors distributed across the panel.

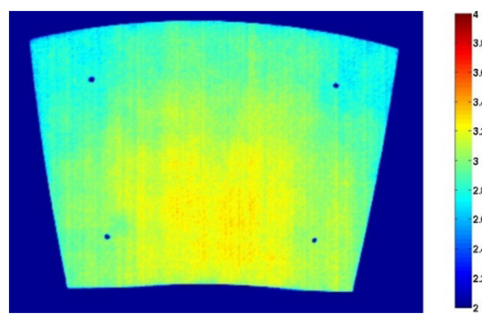


Fig.4Panel temperature increase over ambient.

PROTOTYPING FOR CFRP PANELS

The CFRP prototype panels are sandwich structures using thin CFRP front and back skins (2.5mm thick) and a honeycomb aluminum core (65mm thick), providing high specific stiffness[5]. Two CFRP prototype panels with different sandwich structures are fabricated, one with CFRP side plates on the edge of panel(Panel A) and the other without (Panel B), as shown in Fig.5.

Fig. 5The CFRP prototype panels. Left: with side seal, right: without side seal.

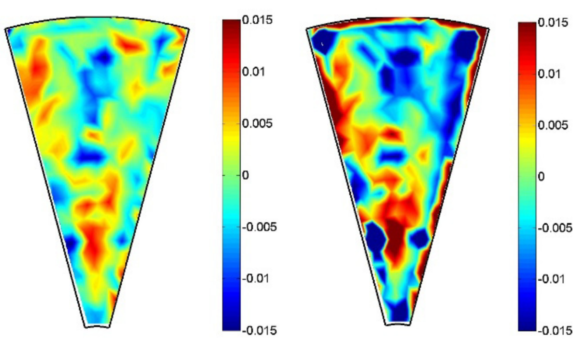
A. *Surface Figure at Low Temperatures*

The same photogrammetric measurement system as for aluminum panel is used. Panel surface figure are measured at several typical ambient temperatures from 40°C to -40°C with the results summarized in Table II.

TABLE IIRMS SURFACE ERROR UNDER VARIOUS AMBIENT TEMPERATURES FOR CFRP PANEL.

Ambient Temperature		T=40°C	T=15°C	T=-10°C	T=-40°C
Panel A	RMS Error (μm)	6.9	5.5	9.5	14.1
	Focal length(mm)	2004.6	1996.2	1985.1	1978.2
Panel B	RMS Error (μm)	8.1	7.3	7.9	8.8
	Focal length(mm)	2000.1	1994.8	1988.7	1980.9

It can be seen from Table IIthat at the lower temperatures the surface error of Panel B increases only slightly after removing the defocusing component. Instead, the surface error of Panel A increases considerably with the decreasing temperature which mainly concentrated on the edges of the panel, as shown in Fig. 6. It indicates that the large surface error of panel A is mainly caused by CFRP side plates. When the ambient temperature drops, the CFRP side plates and the aluminium core experience different amount of contraction in the panel normal direction, resulting large stress and deformation on the front skin.



(a) T=15°C (b) T=-40°C

Fig.6Residual surface error for Panel A after best fitting with a parabolic surface.

Room temperature curing resin is used to reduce the thermal deformation in the replication process. However,the CTE of CFRP skin is still quite large (~$5\times10^{-6}K^{-1}$) because of the high volume ratio of resin, causinglarge variation of the focus length for both panelswhen the ambient temperature changes.We are now investigating on different carbon fiber and resin material to reduce the volume ratio of the resin.

B. *Panel De-icing*

The de-icing heaters are embedded between the upper skin and the aluminum coreof the panel by applying the same kind of resin system, as shown in Fig. 7. The heaters are made of a high conductive CFRP film which itself is laminated between the two isolation layers of glass fiber. High heating efficiency is realized because the distance between the heating film and the reflector surface is small.In order to heat the reflector surface in a uniform fashion, the heating film is segmented and patterned, connected by metal wire, as shown in Fig. 8.Little thermal stress will be generated when the ambient temperature varies due to the material uniformity of the heater and the skin material.

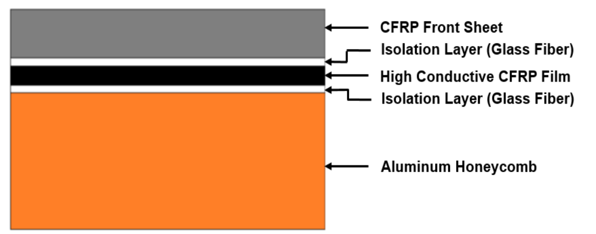


Fig. 7De-icing system of CFRP panel.

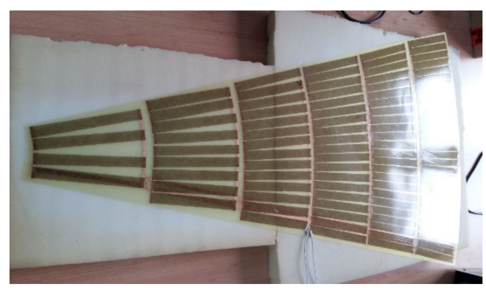


Fig. 8Pattern of the de-icing film heaters.

An input heat flux of 45W/m^2 is applied to the panel, the temperature distribution of the panel front surface obtained by an infrared camera is shown in Fig.9. The average temperature increase is measured to be 2.0°C and the peak-to-valley temperature difference across the panel is less than 0.5°C.

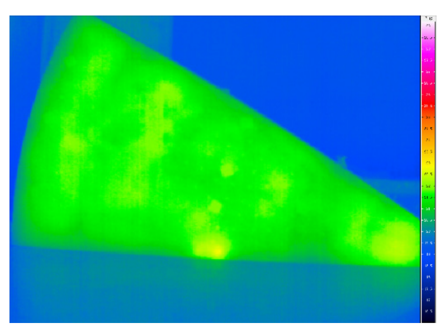


Fig. 9Temperature distribution of CFRP panel for a input heat flux of 45W/m^2.

EXPERIMENTS ON NEAR-FIELD HOLOGRAPHIC ANTENNA MEASUREMENTS

A dual-channel holographic receiver has been developed to demonstrate the near-field holography techinique. Experiment at 92 GHz have been made on a 1.45m test antenna which is a single-piece parabolic dish made from aluminum-honeycomb-sandwiched CFRP. The transmitter is located 63 m away from the antenna on a tower, with an observing elevation around 19 degrees, as shown in Fig. 10.The frontend unit is mounted in the vicinity of the primary focus of an antenna under test, with a signal horn illuminating the reflector and a reference horn, mounted back to the signal horn, pointing to a near-field transmitter. The local oscillator is also mounted inside the frontend unit.

The experiments show that, during the night time at which the ambient temperature doesn't vary rapidly, a 75-minute repeatability (repeating measurement 3 times) of ~2.3 microns rms has been achieved, with an aperture spatial resolution of 46 mm. In order to measure a known surface change, we attached a piece of aluminum foil with a thickness of 43~47 microns to the reflector. By making difference between the holographic measurements before and after the foil attached we obtained a surface change of approximately 45 microns at the foil position, which agrees with the foil thickness, as shown in Fig. 11.

Fig. 10Experimental setup of the near-field holographic measurement

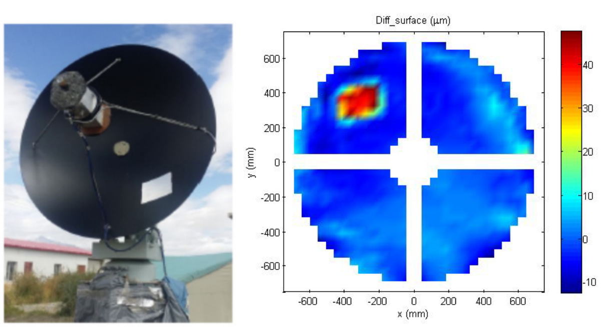


Fig. 11Surface profile measured with two layers of foil

Random errors of the experimental system, such as the pointing error, the amplitude and phase variations of the correlation receiver, have been evaluated and their contributions to the derived surface error have been simulated, indicating that the relatively poor pointing accuracy of the test antenna pedestal is the major contribution to the repeatability, and better repeatability will be expected if the pointing accuracy improves.

During the holographic data processing, we need to fit and remove 6 phase terms (constant, 2 linear gradients in the horizontal and vertical directions, 3 focus translations) from the aperture field. These terms account for a phase offset, an antenna pointing error and a small vector displacement of the signal horn relative to the nominal position. After long-time repeated measurements we have observed regular variations of the fitted terms, which we believe is correlated with the variation of the ambient temperature and solar direction. This implies that if the temperature distribution of the antenna structure is measured simultaneously, we can by this means obtain the relation between the temperature distribution and the variation of pointing and optimum signal horn position. This is very helpful for a telescope to improve its pointing accuracy and aperture efficiency, and also for verifying the related finite element analysis.

CONCLUSIONS

Both aluminium and CFRP panels have been fabricated and tested to evaluate their feasibility for DATE5. No significant additional surface errors of aluminum panel at the low temperatures are found.The structure and process of CFRP panel are still in progress. The performances of CFRP panel at low temperature strongly depends on the panel structure design.The power required for anti-icing for the entire main reflector is less than 1kW for both two types of de-icing systems developed for aluminium and CFRP panels, and the temperature field produced by the de-icing systems have trivial effects on the surface accuracy of the panel.A repeatibility accuracy of 3 microns rms is achieved for the near-field radio holography measurements.Our experiments also shows thatan intentionally introduced surface perturbation can be precisely measured by this technique.

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