Simulation Analysis and Measurement of Solar Radiation Thermal Effects on the Wuqing 70 m Antenna Pedestal (Postprint)

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Abstract

Conducting thermal analysis of solar radiation effects on large-aperture antenna mounts is of great significance for improving antenna pointing accuracy. Taking the 70 m aperture GRAS-4 antenna in Wuqing as the research object, and considering the influences of solar radiation, ambient temperature, and heat transfer, the temperature field and thermal deformation variations of the antenna mount during daytime were obtained. The results show that the temperature field and deformation of the antenna mount are strongly correlated with solar position and ambient temperature, with significant differences in temperature distribution between the sun-facing and shaded surfaces, and also significant differences in temperature distribution for the same beam at different times. The local maximum temperature of the mount is 39.4°C, with a maximum temperature difference of 10.7°C; the maximum deformation is 10.0 mm, the deformation of the mount in the east-west direction is most sensitive to temperature changes, and the overall deformation RMS reaches a maximum of 3.68 mm. Measured results from temperature sensors on the bottom beam indicate that the simulation has high accuracy, with a mean square deviation of 1.1°C between the two. Measured results of axis angle deviation show that the axis angle measurements have significant correlation with variations in the mount temperature field. The simulation results and measured data provide a reference for subsequent improvement of antenna pointing accuracy and structural optimization.

Full Text

Simulation Analysis and Measurement of Solar Thermal Effects on the Wuqing 70-meter Antenna Frame

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Abstract: Analyzing the solar thermal effects on large-aperture antenna frames is crucial for improving antenna pointing accuracy. This study investigates the Wuqing 70-meter GRAS-4 antenna, considering solar radiation, ambient temperature, and heat transfer to characterize the daytime temperature field and thermal deformation of the antenna frame. The results demonstrate that the temperature field and deformation of the frame are strongly correlated with solar position and ambient temperature. The temperature distribution differs significantly between sunward and shadowed surfaces, and the same structural beam exhibits distinct temperature distributions at different times. The maximum local temperature of the frame reaches 39.4°C, with a maximum temperature difference of 10.7°C. The maximum deformation is 10.0 mm, with frame deformation in the east-west direction being most sensitive to temperature variations. The overall deformation RMS reaches a maximum of 3.68 mm. Measurements from bottom beam temperature sensors confirm high simulation accuracy, with a mean square error of 1.1°C between simulated and measured values. Measured shaft angle deviations reveal a significant correlation between shaft angle measurements and frame temperature field variations. These simulation results and measured data provide valuable references for future improvements in antenna pointing accuracy and structural optimization.

Keywords: large aperture antenna; frame; simulation analysis; temperature field; thermal deformation

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1 Introduction

For large-aperture antennas, pointing accuracy is a critical performance metric. Since the structures controlling antenna elevation and azimuth angles are mounted on the frame, frame deformation severely impacts pointing accuracy, making frame simulation essential. The main factors affecting antenna deformation are gravity loading, wind loading, and thermal loading. Gravity-induced linear deformation is typically addressed during the design phase to minimize its impact. Wind loading is generally excluded from frame structural analysis due to the frame's relatively small windward area compared to the reflector. Thermal loading, however, represents a significant research focus because the frame operates continuously in natural environments, experiencing varying solar irradiation at different times and constantly exchanging heat with the surroundings through radiation, conduction, and convection, causing its temperature field to continuously evolve.

Previous simulations and measurements of other antennas have revealed that solar irradiation causes uneven temperature distribution in frames, leading to severe structural deformation. Internationally, Bayley et al. conducted thermal effect studies on the Cambridge MERLIN 32-meter antenna, achieving thermal compensation corrections for pointing based on temperature measurements at key structural locations. Ambrosini et al. investigated thermal effects on a 32-meter antenna, analyzing the relationship between base beam temperature and elevation axis deformation to provide references for antenna improvement. Myung et al. studied thermal effects on the 30-meter TMT telescope structure, using CFD and ANSYS software to simulate the TMT and its environment, predicting hourly thermal deformation over three days. Borovkov et al. established mathematical and 3D finite element models of the temperature field for the RT 70-meter antenna's main reflector, providing detailed descriptions and analyses of temperature variations with particular focus on solar radiation's impact on reflector surface accuracy. Domestically, Wang Hui et al. used FEMAP software to analyze temperature distribution and deformation of the Xinjiang 26-meter antenna frame, finding consistent patterns between measured and simulated results. Chang Wenwen et al. performed structural thermal characteristic analysis on the Xinjiang 25-meter antenna frame using finite element methods, demonstrating that thermal deformation seriously affects antenna pointing. Liu Yan et al. studied the proposed 100-meter telescope for Qitai, Xinjiang, employing transient heat transfer finite element analysis considering solar radiation and convective heat transfer to provide data references for future construction. Kong Deqing et al. investigated the Miyun 50-meter antenna, simulating and measuring the impact of frame temperature distribution on shaft angle measurements, revealing strong correlations.

The Wuqing 70-meter antenna is a critical facility for receiving downlink scientific data from Mars exploration missions. Its mechanical structure comprises primarily the reflector and frame components, as shown in [Figure 1: see original paper]. Currently operating in X, S, and Ku bands with future expansion to Ka band planned, the antenna requires superior pointing accuracy due to Ka band's narrower beamwidth, necessitating thorough investigation of solar irradiation effects on frame deformation.

Following standard procedures for thermal and thermo-structural coupling analysis, this study uses the Wuqing 70-meter antenna as the research object. SOLIDWORKS modeling and ANSYS thermal analysis modules are employed to simulate temperature distribution and deformation throughout a day, focusing on solar radiation and heat transfer. The analysis examines structural deformation effects at different times, validates results with temperature sensor measurements, and analyzes causes of shaft angle measurement deviations to provide references for future antenna improvements and temperature compensation.

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2 Theoretical Framework for Frame Temperature Field Analysis

Radio telescopes operating in natural environments exchange heat with their surroundings through three fundamental mechanisms: conduction, convection, and radiation, forming a transient thermal equilibrium system. This analysis of the antenna frame temperature field is based on heat transfer principles, heat transfer modes, and solar radiation theory.

2.1 Heat Transfer Principles and Mechanisms Thermal analysis follows the First Law of Thermodynamics (energy conservation). The transient thermal equilibrium equation is:

$$C(T)\dot{T} + K(T)T = Q(T)$$

where $C(T)$ is the specific heat matrix representing internal energy increase, T is the nodal temperature vector, $\dot{T}$ is the time derivative of temperature, $K(T)$ is the conductivity matrix incorporating thermal conductivity, convection coefficients, emissivity, and shape factors, and $Q(T)$ is the nodal heat flow rate vector including heat generation.

The 70-meter antenna frame temperature field involves three heat transfer mechanisms: conduction, convection, and radiation. Conduction refers to internal energy exchange within or between beams due to temperature differences, dependent on material properties and temperature gradients. Convection occurs when a solid contacts a moving fluid at different temperatures, with the fluid transferring energy to or from the object, and can be natural or forced. The convective heat flux density q_c between the frame and surrounding air is:

$$q_c = h_c(T_a - T_{sur})$$

where h_c is the convective heat transfer coefficient, T_a is the structure surface temperature, and T_{sur} is the ambient temperature. The coefficient h_c is determined by:

$$h_c = 3.83v + 3.67 \quad \text{(for outer surfaces)}$$
$$h_c = 3.5 \quad \text{(for inner surfaces)}$$

where h_c has units of $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$.

Thermal radiation is energy exchange through electromagnetic emission and absorption by other objects, requiring no medium and increasing with temperature. The radiative heat flux density q_r between the frame and surrounding air is:

$$q_r = \varepsilon\sigma(T^4 - T_{sur}^4)$$

where ε is the surface emissivity coefficient ($0 \ll \varepsilon \ll 1$) and σ is the Stefan-Boltzmann constant ($5.66 \times 10^{-8}\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$).

2.2 Solar Radiation Theory Radiation acting on the frame structure originates from direct solar radiation, sky diffuse radiation, and ground-reflected radiation, with direct solar radiation being predominant.

Direct solar radiation on the structure depends on solar altitude angle, azimuth angle, and the angle between the structural surface normal and solar incidence direction. Solar altitude (α) and azimuth (β) angles are given by:

$$\sin\alpha = \sin\phi \times \sin\sigma + \cos\phi \times \cos\sigma \times \cos\omega$$
$$\cos\beta = (\sin\phi \times \sin\alpha - \sin\sigma) \times \sec\alpha \times \sec\phi$$

where σ is the declination angle, ω is the hour angle, and ϕ is the geographic latitude. Declination and hour angles are expressed as:

$$\sigma = 23.45^\circ \sin\left(\frac{284 + N}{365}\right)$$
$$\omega = 15^\circ(-12 + t)$$

where N is the day number starting from January 1 and t is the hour of day. Solar radiation intensity at the top of Earth's atmosphere is:

$$I_S = I\left(1 + 0.034\cos\frac{360N}{365}\right)$$

where I is the solar constant, taken as 1367 $\mathrm{W \cdot m^{-2}}$. Solar radiation on a plane perpendicular to the incidence direction at ground level is approximated by:

$$I_0 = I_S \sin\alpha\left(\sin\alpha + \frac{1 - P}{1 + \sin\alpha}\right)$$

where P is the atmospheric transparency coefficient, varying with weather conditions (typically 0.53–0.85).

Direct solar radiation on the frame surface is:

$$I_d = I_0 \cos\theta$$

A portion of solar radiation is absorbed, scattered, and reflected by the atmosphere, uniformly projecting onto ground structures independent of surface orientation. Diffuse solar radiation is:

$$I_a = I_h \frac{1+\cos\gamma}{2}$$

where γ is the surface inclination angle and I_h is diffuse radiation on a horizontal surface:

$$I_h = (I_S \times 0.271 - 0.294 I_0)\sin\alpha$$

Ground-reflected radiation from direct and diffuse components is:

$$I_f = (I_0 + I_h) R_s \frac{1-\cos\alpha}{2}$$

where R_s is the ground reflectivity, approximately 0.2.

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3 Simulation and Measurement of Solar Thermal Effects on Frame Temperature Field

The 70-meter antenna is located in Wuqing, Tianjin at 39.536°N, 117.099°E, with an altitude of approximately 10 m. The analysis date is June 5, 2021, with maximum temperature 33.0°C, minimum temperature 18.0°C, and wind speed of 3–4 on the Beaufort scale. The antenna was in stowed position at azimuth 0° and elevation 90°. Solar radiation intensity on a horizontal plane was calculated for different times using the theory from Section 2, becoming zero after 20:00 when solar altitude falls below 0°, as shown in [Figure 2: see original paper].

SOLIDWORKS software was used for geometric modeling, with the model imported into ANSYS and meshed using SOLID186 and SOLID187 elements. Thermal analysis was performed based on boundary conditions. The frame consists primarily of three types of box-section beams: 800 mm × 800 mm, 800 mm × 1000 mm, and 800 mm × 1500 mm, with wall thickness of 25 mm. The frame features planar symmetry, comprising two "A"-frame beams, diagonal support beams, bottom beams, and a second-level platform, as shown in [Figure 3: see original paper]. The frame material is ordinary low-alloy steel [10] with properties listed in . Considering the zinc-rich primer coating, the surface radiation absorptivity is taken as 0.5.

3.1 Frame Temperature Field Analysis Based on the theoretical framework and simulation environment, heat flux densities, convection, and radiation coefficients were calculated for different times. Transient thermal analysis was performed from 06:00 to 21:00, considering reflector shading on the frame. To reduce computation time, solar radiation was applied in 2-hour load steps while convection coefficients and ambient temperature were applied in 1-hour steps, yielding the frame temperature field at various times.

Simulation results for the frame temperature field are shown in [Figure 4: see original paper], where axis X points north, Y points west, and Z is vertical. Temperature variations exhibit a rising then falling trend from east to south to west as the sun position changes. During 09:00–11:00 and 13:00–16:00, temperature distributions differ significantly between east and west sides. At approximately 16:00, the frame reaches its maximum local temperature of 39.4°C, with the sun positioned southwest of the frame. High temperatures appear primarily on the west side of lower diagonal beams and the west side of “A”-frame beams. After 17:00, temperatures across all beams gradually converge. Notably, beam connection points have larger air contact areas facilitating heat exchange, resulting in lower temperatures than surrounding regions.

[Figure 5: see original paper] presents simulated temperature variations over time. Maximum and minimum temperatures follow similar trends, responding to ambient temperature and solar radiation changes. Frame temperatures rise significantly from 07:00–16:00 due to increasing ambient temperature and solar radiation intensity. The maximum temperature difference between beams increases rapidly after 06:00, stabilizes, then decreases after 14:00, reaching 1.9°C by 21:00. The peak difference of 10.7°C occurs around 14:00.

3.2 Thermo-Structural Coupling Analysis Due to external displacement constraints, temperature field changes induce strain and displacement—thermal strain and deformation. Based on the temperature distributions from Section 3.1, thermo-structural coupling analysis was performed. Considering frame self-weight and reflector gravity, the reflector mass (900 t) was applied to “A”-frame contact surfaces. Full displacement constraints (all degrees of freedom = 0) were applied at drive wheels (two southern bottom wheels), vertical displacement constraints at driven wheels (two northern bottom wheels), and axis Z displacement constraint with axis X and Y rotation constraints at the azimuth axis position to determine deformation at different times.

[Figure 6: see original paper] shows partial frame deformation simulation results. Compared with [Figure 4: see original paper], deformation does not completely follow temperature field changes. At 08:00, while temperatures are high on the east side of the eastern “A”-frame and east side of the western upper diagonal beam, deformation at the top of the western “A”-frame exceeds twice that of the eastern “A”-frame, indicating that upper diagonal beam temperature changes significantly affect “A”-frame top deformation. At 12:00, both “A”-frame beams show large deformation. Despite small temperature differences at the “A”-frame tops, large temperature differences at the bottom structures accumulate to produce substantial top deformation. At 21:00, after sunset, frame cooling occurs and deformation becomes primarily gravity-driven. Overall, east-side deformation is prominent in the morning, west-side in the afternoon, with symmetric east-west deformation at noon. Sunlit areas exhibit significantly greater deformation than shaded areas.

Maximum deformations in each direction are shown in [Figure 7: see original paper]. East-west deformation follows the same trend as total deformation, being most temperature-sensitive. North-south deformation fluctuates around 2.3 mm and vertical deformation around 3.9 mm, both less temperature-sensitive. Maximum east-west deformation is 10.3 mm, occurring near 18:00 when the sun directly irradiates the west side while the east side is completely shaded, creating extreme east-west temperature asymmetry. With ambient temperature near 32°C (close to the daily maximum of 34°C), maximum daily deformation occurs around 18:00. As shown in [Figure 6: see original paper], frame deformation results from combined gravity and temperature field effects.

To characterize overall deformation, RMS deformation is calculated as:

$$\mathrm{RMS} = \sqrt{\frac{\sum_{i=1}^{n} X_i^2}{n}}$$

where n is the number of nodes and X_i is the thermal deformation at each node. Structural analysis without temperature field was also performed for comparison, as shown in [Figure 8: see original paper]. Without temperature field, frame deformation RMS is 3.06 mm. With temperature field, overall deformation decreases from 08:00 due to the reference temperature of 22.0°C being lower than frame temperature during 08:00–10:00, then increases with enhanced solar radiation and ambient temperature, peaking at 3.68 mm at 16:00 when thermal deformation is most severe, before decreasing with reduced temperature and solar radiation.

3.3 Temperature Sensor Measurement Results To validate simulation results and establish temperature-pointing compensation models, three PT100 platinum resistance temperature sensors were installed on the frame bottom beams. Measurements were taken on June 5, 2021, with sensors located on the north face of the northern bottom beam, south face of the southern bottom beam, and east face of the eastern bottom beam, as shown in [Figure 9: see original paper]. Measurement accuracy is 0.1°C [20]. [Figure 10: see original paper] compares simulated and measured bottom beam temperatures, showing similar trends with some deviation. The mean square error between measured and simulated values is 1.1°C, indicating high simulation accuracy. Deviations arise from: (1) fixed simulation parameters not adjusting to real-time environmental changes such as wind speed and ambient temperature; (2) consideration of only reflector shading, not inter-beam shading.

3.4 Shaft Angle Deviation Measurement Results The 70-meter antenna features elevation and azimuth angle measurement using absolute encoders (RCN8510) with 1 system accuracy in a sealed, environmentally controlled space with regulated humidity and temperature, measuring once per second [10]. Environmental changes cause frame deformation, producing small shaft angle variations recorded by the measurement system.

[Figure 11: see original paper] shows shaft angle measurements on June 5, 2021. Nighttime deviations are near zero. From 06:00, elevation and azimuth deviations appear, with absolute values increasing then decreasing then increasing again. After 21:00, deviations approach zero as the sun sets. Maximum absolute azimuth deviation is 16.2 and maximum elevation deviation is 26.28 . Elevation angles, directly connected to the large-wind-area reflector, are more wind-sensitive than azimuth angles, producing numerous peaks in the elevation deviation curve. Comparison with [Figure 5: see original paper] reveals significant correlation between azimuth deviation and frame temperature distribution. [Figure 5: see original paper] shows temperature distribution symmetry about the north-south axis, with high east-side temperatures in the morning and west-side in the afternoon, while azimuth deviation curves show opposite morning-afternoon variation directions.

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4 Conclusions and Future Work

This study performed simulation analysis and measurements on the Wuqing 70-meter antenna frame, analyzing temperature distribution and thermal deformation, conducting temperature sensor measurements on bottom beams, and analyzing shaft angle measurement deviations, revealing clear patterns.

Simulation results show that daily temperature field variations result from combined ambient temperature and solar radiation effects. At 16:00, the west side of lower diagonal beams and west side of "A"-frame beams reach maximum temperature (39.4°C), with RMS deformation also peaking at 3.68 mm, representing maximum impact on antenna pointing. Maximum temperature difference changes rapidly around sunrise and sunset, stabilizing midday, with a peak of 10.7°C around 14:00. East-west deformation follows total deformation trends, reaching 10.0 mm maximum. North-south and vertical deformations are less temperature-sensitive, fluctuating around 2.3 mm and 3.9 mm respectively. Upper diagonal beam temperature changes significantly affect "A"-frame top deformation.

Measured data show temperature simulation results match actual measurements with 1.1°C RMS error, confirming high accuracy in reflecting frame temperature field variations. Deviations stem from: (1) fixed simulation parameters not adapting to environmental changes; (2) consideration of only reflector shading, not inter-beam shading. Shaft angle deviations correlate significantly with frame temperature field, with elevation angles more wind-sensitive than azimuth angles.

Future work will install temperature sensors on additional beams for comprehensive temperature field monitoring and establish mathematical models correlating shaft angle deviations with frame temperature field to enable temperature compensation for improved antenna pointing accuracy.

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