Initial Considerations of the 5 Meter Dome A Terahertz Explorer (DATE5) for Antarctica

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Abstract- **Terahertz radiation comes from cold objects in universe. It provides important information of star and galaxy formation. Within these bands, thousands of molecular lines are located, which may reveal important processes in cosmology. In Antarctica, the Dome A area has the best observing windows in the terahertz waveband. In this paper, a 5 meters Dome A Terahertz Explorer (DATE5) telescope concept is provided, which is a fully steerable telescope, working under the harsh Dome A polar environments. It requires a higher surface and pointing accuracies. This paper also discusses major aspects to be taken into consideration in its initial conceptual study.**

I. INTRODUCTION

In the electromagnetic wave spectrum, terahertz radiation, which lies between very far end of infrared and just before the start of microwave radiations, is a unique band for astronomer to observe the cold universe between 4K and 100K[1].

If one wish to know the formations of heavy elements, stars, planets, and galaxies, it is very important to make observations in the terahertz frequencies. In astrophysics, one key issue in the big bang theory was the early life of galaxies. The galaxies we see today are in optical wavebands. However, there must have been a time the galaxies first formed in the universe, radiation from these early galaxies would be in the infrared band and had highly redshifted blackbody spectrum. These radiations would be redshifted into the terahertz band as we observe them today.

The cosmic microwave background (CMB) radiation peaks in the range of 100 to 300 GHz, which lies at the bottom of terahertz frequency range. However, the measured anisotropy has revealed the acoustic modes in the early universe. In the new century, to measure the predicted complicated state of polarization of CMB would reveal the physical mechanism when the radiation became decoupled from matter, and the rest being formed as gravity waves in the earliest moments of creation.

The terahertz region of spectrum is also essential for astronomers in decoding the secrets of star formation. Many thousands lines are now known in the THz bands. By mapping and studying these lines, it is possible to build complete models of objects; these models include temperature, density, movement of material, magnetic field, etc. All these make the terahertz observation and terahertz telescope construction being extremely important.

Before building a successful terahertz telescope, two important issues are the receiver technology and the site selection. Terahertz receiver technology is mainly driven by applications in astronomy. In China, a design team at Purple Mountain Observatory had finished a 500GHz SIS (superconductor-insulator-superconductor) receiver in 2005[2]. The team is now working on the terahertz receiver study. On the site selection issue, a team of Chinese scientists had reached the Dome A plateau in Antarctica also in 2005. The Dome A area is 4,093 m above sea level. The water vapor contents of the site are very low with a year average number of 0.21 mm[3],[4],[5]. Therefore, Dome A provides a rare atmosphere windows between 0.7 and 1.6 terahertz. The transparency of the Dome A is not only higher than that of the Acatama (5105 m above sea level) and Staircabar (5525 m above sea level) sites in Chile, but also higher than Dome B, C, and F in Antarctica[6]. At Dome A, a high quality terahertz telescope can conduct scientific research that would otherwise only be possible from space.

Based on these listed conditions, in 2010 astronomers at Purple Mountain Observatory proposed a two-step plan: first to build a 5 m terahertz telescope and, then, to build a follow-up 15 m terahertz telescope. The 5 m proposed telescope is now named as 5 Meter Dome A Terahertz Explorer, abbreviated as DATE5 telescope.

II. ENVIORMENT CONDITIONS AT DOME A

The recorded annual temperature variations at Dome A, Antarctica, are ranged from -10°C to -80°C with a diurnal variation smaller than 15°C. In summer, the temperature is about -30°C, so that ordinary power machines could work reliably. However, after about a month, the temperature will fall down to very cold region, where no snowmobiles could even start. The year round average temperature is -58.4°C. The vertical temperature gradient is generally smaller than 2°C/m above the inversion layer. Dome A also has a smaller inversion layer and smaller seeing size.

The average wind speed at Dome A is only about 2.5 m/s with the maximum speed of about 14 m/s[7]. Since the site is 4000 m above sea level, the air pressure is lower. The variation of air pressure in the area is between 540 and 610 hPa with an average value of 575 hPa. Low air density will make convention cooling less efficient. Lower air density brings lower oxygen level. This brings difficulties in human activities.

Air relative humidity is ranged between 10% and 80% with an average relative humidity of only 40% at Dome A. These numbers do not give direct indication of the absolute water contents in the air as they are relative to the maximum allowable water contents at the temperature. At a low temperature the maximum water contents allowable are very small. Snowing is not often at the site and the average snow accumulation is about 23 mm equivalent water every year. Frosting and icing have been seen on top of some over-winter observing instruments.

International shipping of the telescope parts will be provided by XueLong ice breaker, which arrives at Zhongshan Station, a year round seashore station, and the cargo will be subsequently transferred to surface transportations by snowmobiles. A one way surface shipping takes 18-20 days from Zhongshan to Kunlun Station over a 1,200 km journey. The trip can be only performed in summer time.

Telescope assembly will be finally carried out at Kunlun Station of Dome A. As a summer supporting station, Kunlun station could provide accommodations of about 20 people up to one month. There is no winter over stuff in this mountain station. Therefore, only small part of the observation data cumulated can be transferred to observer’s home in real time while bulks of data are retrieved by the summer traversers.

III. DESIGN CHALLENGES OF DATE5 TELESCOPE

The proposed DATE5 telescope will include two important bands: Band 1 of 0.78~0.95 THz using SIS receiver and Band 2 of 1.25~1.55 THz using SIS/HEB (hot electron bolometer) technology[8],[9]. Both receivers are in the developing stage.

For antennas working in this very high terahertz frequency, the reflector surface root mean square error has to be smaller than one twentieth of the wavelength operated. The pointing accuracy should be about one tenth of the telescope’s main beamwidth[1]. For cancelation of noise from the atmosphere, small fast chopping mirror or chopping secondary mirror may be needed for this telescope. By considering the wide temperature variation, very low temperature, and very low air density of the Dome A site, the above accuracy and fast chopping requirements produce real challenges to the telescope designers.

Stable surface shape under a wide temperature range is usually a problem when materials with high coefficient of thermal expansion (CTE) and low heat conductivity are used. Panels with stretched aluminum skin and stiffening ribs glued with epoxy are not suitable for this telescope as the epoxy has lower heat conductivity. Machined aluminum panels may be a suitable dish panel candidate for this telescope. However, the size of the aluminum panels may be limited when a carbon fiber reinforced plastics (CFRP) backup structure (BUS) is used. Other suitable panel candidates include CFRP replicated sandwich panels with aluminum honeycomb. These panels have been used in submillimeter wavelength telescopes in the past.

Generally, low CTE CFRP material has to be used for the BUS structure of this telescope as the site temperature varies from -10 to -80^{o}C. The BUS can be either in truss or boxed forms. To avoid temperature gradient inside the telescope BUS structure, forced ventilation can be applied to keep the temperature uniform inside. Air ventilation can also be used inside the receiver cabin and the mounting structures. The low air density of the site will reduce the efficiency of all power equipments of the telescope[10]. However, the lower site air temperature will help the heat exchange for power equipments. These effects may cancel each other.

Other design difficulties of the DATE5 telescopes include the anti-frost requirement, stable working temperature for receiver and telescope drive system, limited installation time, and long period remote operation of the telescope.

Frost is one important issue in the telescope design as the frost may block terahertz wave path, damage telescope structure, and stop movement of the drive train. When a solid surface is chilled below the dew point of the surrounding air, frost will be formed on the surface.

Frost is a form of ice crystals growing directly on the structure surface. The crystals size may be different depending on time, temperature, and the amount of water vapor available. Cooling of structure surface is the cause of the frost forming. Radiation and wind are two main reasons in structure cooling. When the structure has sharp edges, holes, or gaps, the structure relative surface area per structure weight is larger than that in other regions. These surfaces will cool down faster due to radiation or air convection. Holes and gaps also attract ice particles and make ice and snow build up.

Structure material and surface coating influences frost forming. Water is a polar molecule with a surface energy of 72 mJ/m^2. It attracts molecules with the same polar property or with higher surface energy. Metals have surface energy of about 500 mJ/m^2 while Teflon or wax have low surface energy. Surface with high surface energy is contaminated easily with low surface energy material. Modern anti-frost coating uses polypyrrole to avoid ice to form on structure surface.

One can also apply heating elements to prevent frost. Profiling the structure to avoid any holes, gaps, and sharp edges is effective in keeping the structure surface temperature stable. Icing may be also caused by ice particles carried by the wind or by interaction of strong temperature changes caused by weather.

To maintain a stable temperature for receiver and drive system, local heating, internal ventilation, and wall insulation are necessary, so that the telescope can be divided into different temperature zones to meet individual zone temperature requirement for different systems.

The DATE5 telescope should have limited number of pre-assembled components before it is shipped to Dome A. The connection and adjustment between components should be simple and easy so that the telescope site assembly can be finished within short period.

IV. DESIGN FEATURES OF THE DATE5 TELESCOPE

A. Optics of the antenna

A classic Cassegrain or an R-C optical systems can be used for DATE5 telescope. An R-C system has a slightly larger field of view, but requires fixed mirror surface shape and mirror separation. Therefore, traditional Cassegrain design is still preferred. In the optics design, the size of subreflector should be slightly larger than it should be, so that the beam pattern will be better when a mirror chopping is applied.

It is preferred to use a two mirror system, resulting in higher efficiency and lower noise level than those of three- or four-mirror systems. However, chopping of the subreflector increases telescope cost because all the subreflector drive and encoder systems are on top of the dish, suffering from Antarctica weather changes. For eliminating the reaction force from subreflector chopping, complex reactionless drive system has to be used. To avoid subreflector chopping and the motion of receiver Dewar, Coude optical system with two additional small mirrors may be used. This system can be easily arranged inside a slant axis mounting structure, resulting in a smoother telescope profile without sharp edges, holes, and gaps.

B. Mounting and structure design

In ground layer, air turbulence at Dome A is serious; the antenna dish should be high above the ground. Therefore, the telescope has a tall base. The distance between the ground level and the elevation axis is about 5 meters. Ice has a small compression strength. The average pressure on the ice surface have to be kept lower than 403 Pa and the maximum pressure on the ice surface under survive force condition should be lower than 470 Pa[11]. In order to reduce forces from telescope steel structure on the ground ice surface, timber footing may be used under the steel structure surface and on top of ice surface. Timber has a Young’s modulus of about 6.9×10^9 Pa. For long term stability, the footing of the telescope has to be buried under ice surface.

Both altazimuth and slant-axis mountings can be used for the DATE5 telescope. In an altazimuth mounting, receiver is located at Cassegrain focus. The weight of the receiver cabin is used to balance the dish structure weight. The elevation axis usually uses self-adjusted spherical roller bearings. The azimuth axis will use a double row roller bearing. However, there are gaps existed between yoke and cabin. The ice particles could be trapped in these gaps, blocking the required telescope movement. Therefore, anti-frost heating has to be applied in these areas.

Slant axis design has a much smoother profile without any sharp edges, holes, or gaps for frost to stay. Slant axis mounting includes two axes: one is slant axis and the other is slant-muth axis. The slant-muth axis is the same as azimuth axis in an altazimuth mounting. The name here is specially for slant axis mounting system. All the telescope drive system is within one structure volume. Two identical bearings and drive gears can be used for both the slant-muth and slant axes. If the receiver is at the Coude focus, all the cables and pipes connected to delicate Dewar device are fixed with slant-muth platform. No relative motions are required for the receiver parts cables, and pipes. The whole antenna forms a closed volume which makes telescope thermal control and frost prevention easier. The space inside the telescope volume can be divided into different temperature zones: a warm zone in the main body and a cold zone in the BUS area. With each zone, the temperature is the same and, between different zones, the temperatures are different. The waste heat generated from electronic or electrical parts is used for internal heating.

C. Dish and surface panels

For terahertz observation, high precision surface panels and CFRP backup structure may be necessary. The surface panels can be either computer control machined aluminum ones or replicated CFRP honeycomb sandwiched ones. The machined aluminum panels are weight reduced from solid thick aluminum alloy plates. The replicated CFRP sandwiched panels are formed on top of a precision glass mould. The backup structure can be either CFRP trusses or CFRP box structures.

Reflecting surface error of the DATE5 telescope comes from a number of sources: panel, BUS, and secondary mirror. These error sources also include manufacture, gravity, thermal, wind, and even the measurement itself. The thermal induced panel or BUS error includes two different temperature distributions: 1) absolute temperature error and 2) differential thermal error. Absolute temperature error, also named as temperature soaking error, is caused by the CTE difference between panel and BUS materials. The error is produced as the surface setting temperature is different from the operation temperature. Differential thermal error is caused by temperature difference between different parts of the same panel or BUS structure. Reduced stiffness of the panel adjusters in one or more directions can take care of part of the absolute temperature surface error, while panel material conductivity can affect the panel differential thermal error. To reduce the BUS differential thermal error, low CTE CFRP material has to be used in this structure.

The main component of CFRP is carbon fibers. Within carbon fibers, carbon atoms are in a form of hexagonal layers with very strong bonds between atoms. These layers form rings around fiber axis. In the fiber axial direction, Young’s modulus is very high up to many hundred GPa, few times of that of steel. In the perpendicular plane, the modulus is few times smaller. Carbon fibers also have very low, even negative, CTE along the fiber direction. Carbon fibers are held together by polymer resins. Resin usually is poorer in stiffness as well as in CTE, resulting in less stiffness and thermal unstability in the resin direction.

CFRP BUS structure can be truss style made of tubes or box style made of plates. When using truss structure, joints are usually of stainless steel, adding more weight and more thermal expansion, or Invar, adding more cost. All the panels and CFRP BUS structure has to be tested in a low temperature chamber before being used in the DATE5 telescope.

D. Thermal control of the telescope

At Dome A, the temperature is very low (between -20 to -80^{o}C), too cold for operation of receiver, drive and control systems. Under this condition, some components of the systems may be not functioning. In general, receiver cabin requires temperature higher than that at Dome A site. The drive system can have a slightly lower operation temperature. The BUS area can be even lower. Most telescope volume should keep a constant temperature to avoid structure distortion.

Entire telescope body should be insulated using forms and reflecting plates. Heating elements may be needed on panels for frost prevention.

E. Drive and control systems

To maintain an accurate pointing of the DATE5 telescope, backlash free twin gear drive system will be used for both telescope axes. All the motors, gear boxes, and encoders have to be pre-tested in cold chambers before been assembled into the telescope. Closed loop control is used for good pointing and tracking. Before the telescope operation, the pointing correction is carried out using radio as well as optical stars with known coordinate positions.

F. Test operation and site assembly

When the DATE5 telescope is finished, it will be transported to Delingha observing station in west China for the system pre-assembly and testing. All assembly procedure has to be checked to meet the site assembly requirement. This requires using standard interfaces for connections between components. Therefore, the parts can be quickly assembled and detached. Dish surface holographic measurement in Delingha is one important task.

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