RADIO TELESCOPE ENGINEERING: THE 40 METER IGN ANTENNA

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Abstract: Large fully steerable radio telescopes are extensively used for radio astronomy and geodetic applications in the microwave and millimeter wave range. Single dish, connected interferometry and (very long baseline interferometry) observational techniques involve the construction of big collecting areas with high precision drive systems, high precision surfaces, ultra-high sensitivities and complex electronic processes.

In this document we intend to review some of the main aspects in the design and construction of large size and high precision surface radio telescopes. We will discuss different engineering topics and illustrate them with examples based on our experience with the construction of the 40 meter IGN radio telescope.

1 Introduction

The radio telescope construction involves many fields of engineering. Civil works, optical, radiofrequency, electronics, software and mechanical engineering need to be coordinated in order to obtain a big collecting high precision surface with highly accurate pointing. A big effort on mechanical engineering is needed for the design of the structure that supports the reflector, with ratios between surface rms accuracy and antenna diameter in the order of 10^6. A high precision mechanical system with very accurate servomechanism design are also needed to obtain pointing accuracy in the order of arcseconds with structures having dead weights of nearly 500 tons.

Figure 1: The IGN 40 meter radio telescope.

Good electromagnetics (optical and radiofrequency) and cryogenics skills are also needed. The design of the optical geometry of the system and of the feeds that illuminate the main reflector plays a crucial role in the antenna performance. Highly sensitive receivers involve the development of cryostats and low temperature instrumentation.

Complex software engineering is also present in servo control as well as in remote control sessions. Finally low frequency electronics and data processing add to this always growing list of engineering tasks.

The IGN (Instituto Geográfico Nacional from Spain) is building a 40 meter radio telescope at Yebes (Guadalajara) that will be used for geodetic and astronomic VLBI (very large base line interferometry) and single dish observations. The radio telescope will cover the frequency band from 2 to 120 GHz with an expected aperture efficiency of 50% and an angular resolution of few seconds at the highest frequency.This radio telescope will increase the capabilities of the EVN (European VLBI Network) and complement other existing radio telescopes, for example the IRAM 30 meter radio telescope at the lower frequency range.

Larger collecting areas, with higher angular resolutions and sensitivities, are the subject of international projects such as SKA [1] (Square Kilometer Array) or ALMA [2] (Atacama large Millimeter Array). The IGN is also participating on these projects which involves smaller but more precise antennas and other challenging technologies.

2 Optical design

A diverse range of axially symmetric antenna configurations are widely used, the most common being the Cassegrain configuration. A hyperboloidal subreflector is interposed between the paraboloidal reflector and its focal point, providing a constant path length for the rays from the feed (at the system focus) to the aperture plane. This or other designs based on this one, are very appropriate configurations because of their high efficiency, low aberrations, low noise system temperature performance and easy accessibility to electronic receiver equipment.

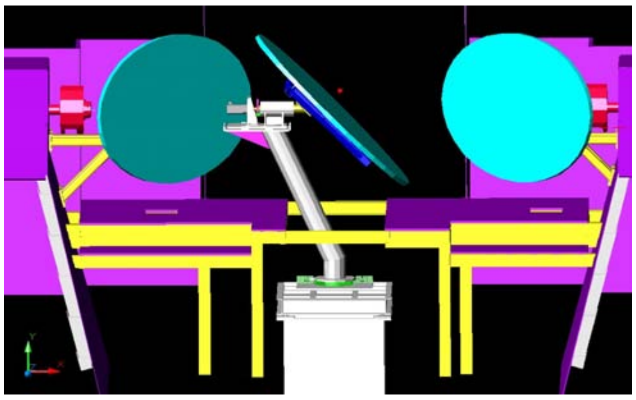

Figure 2: Nasmyth mirror configuration of the 40 meter IGN radio telescope.

The IGN 40 meter radio telescope, Figure 1, is a Nasmyth-Cassegrain system, a modification of the basic Cassegrain design [3], with high equivalent focal ratio, F/D=7.9, high magnification, M=21, and a Cassegrain focus placed 11 meters away from the vertex of the parabola. The beam passing through the main reflector vertex hole encounters the Nasmyth mirror, M3, and it is deflected 90 degrees from the optical axis along the (fixed) elevation rotation axis of the antenna. M3 mirror moves in elevation compensating the antenna movement. The electronic equipment is then free from the elevation movement of the antenna and remains fixed inside the azimuth rotating cabin.

Two flat mirrors, M4 and M4', are placed at both sides of M3 and redirect the beam to the receivers. The M3 mirror can be rotated 180^o, choosing one of the mirrors, Figure 2. This configuration increases the number of receivers that can be accommodated in the receiver cabin.

Once the geometrical design is fixed, the RF synthesis and analysis is made using methods such as Physical Optics (PO) or Ray-tracing. The first is the method usually employed in the analysis of the radiation characteristics of multireflector systems in the microwave and millimeter range. It is based on the calculation of currents on each reflector and is by far the most accurate, although at the expense of computation time. GRASP [4] is a well known commercial software based on this technique. At the other end of the spectrum is ray tracing which ignores diffraction effects entirely.

The design of the feeds or the reflectors placed on the focal zone can be achieved with Gaussian beam techniques or quasioptics [5]. Gaussian beam analysis is a very powerful, fast and easy to understand tool that can be accurate enough to design complex multireflector systems. It uses an appropriate set of expansion functions to model the field between reflectors. Gaussian beam analysis is adequate for radio telescopes with high F/D ratios and gaussian feeds. The most gaussian feed is the corrugated feed horn [6]. Most of the radiastronomy feeds are based on this design.

In practice most of the designs start with a feasibility study by ray tracing, are designed with gaussian beam optics and are finally tested with PO. This is the case of the M4' branch of the 40 meter radio telescope, Figure 3. A complex system with up to seven receivers, focusing mirrors, lenses and flat and dichroic mirrors has been designed using quasioptics and has been tested using GRASP.

3 Mechanical design

The basic specifications in the mechanical design of a radio telescope are the pointing accuracy and the reflector surface accuracy. Typically, the pointing accuracy is around 10% of the half power beam-width and the surface accuracy around the 5% of the wavelength. For the 40 meter radio telescope this means 5" for the pointing and 150 microns rms for the surface accuracy.

The antenna structural design, Figure 4, is usually carried out by finite element analysis (FEM) [7] and covers the following tasks: determine the structural elements and construct a model, analyze the stiffness of the structure, calculate deformations, analyze the natural frequencies and calculate the pointing error under gravity, thermal and wind loads.

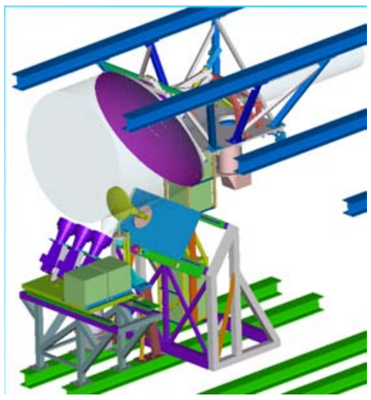

Figure 3: M4' optics.

This analysis is usually specified under three sets of wind conditions: operation, steerable and survival winds. For the 40 meter radio telescope four wind condition ranges have been specified: operation below 10 m/s, degraded operation below 15 m/s, steerable to stow position below 20 m/s, maximum steerable to stow position at 33 m/s and survival wind at 50 m/s.

One of the most difficult problems in the structural design of large antennas is the prevention of reflector surface deformation due to dead weight and wind loading. In designing large antennas, better surface accuracy is obtained by designing the structure so that the reflector surface deforms from one paraboloid to another when rotated in elevation. This is known as homologous deformation [8].

A homologous structure is designed for optimum performance under light wind conditions and without temperature effects. Therefore when very high surface accuracy is required special precautions must be taken to maintain a uniform temperature distribution. The rear side of the back-structure must be covered with thermal insulation panels and fans must be provided for fixed air circulation in the space between the reflector panels and the insulation panels.

Another important issue is related to the natural frequencies, which are the main factor that determine the response to variable loads such as non static winds and earthquakes. We aim to achieve high natural frequencies to reduce the effects of time varying loads. However for larger antennas the mass increases more rapidly than the stiffness and high frequencies cannot be achieved easily. A large antenna is designed so that the natural frequencies are greater than 2 Hz, as it is the case for the 40 meter radio telescope. On the other hand, having low resonant

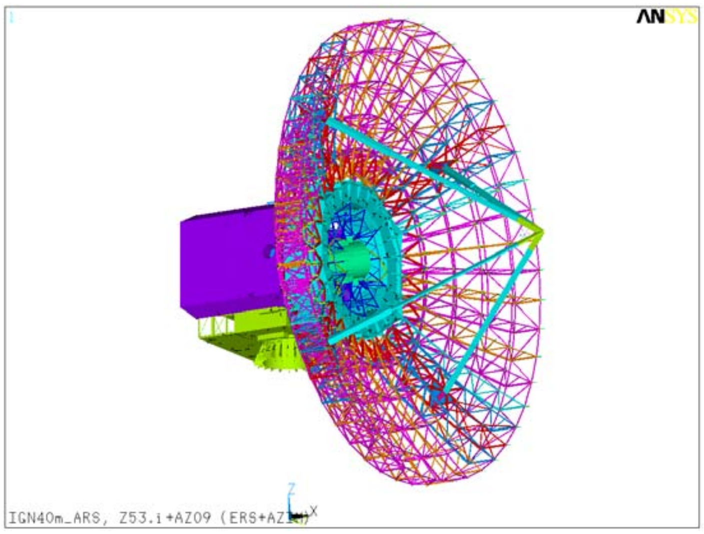

Figure 4: Mechanical FEM model for the 40 meter IGN radio telescope.

frequencies also reduces the complexity of the servo loop, mainly because the bandpass of the servo must be lower than the lowest resonant frequency of the antenna to prevent violent instability [9].

4 Mechanical description

The antenna mechanical system is composed of three main units: reflector assembly, antenna mount, and drive system.

Fully steerable antennas have been often designed in the elevation over azimuth axis configuration which is the most economical. For microwave mounts, large diameter bearings are used to form the axis about which the antenna rotates in azimuth angle. For larger antennas, azimuth rotation is provided by a circular track with wheels at the base of a large frame called the alidade. These are very rigid mounts where track diameter and support frame structures can be very large, maintaining wind effect low and resonant frequencies high. However there is a high cost of leveling the rail and for the foundations. Nowadays, the bearing fabrication is competitive and presents the only drawback of the hypothetical replacement if damaged.

The design of the 40 meter radio telescope, Figure 5, is based on the concept of a turning head antenna with both axes, elevation and azimuth, implemented with roller bearings and geared drives. The telescope, made of steel, is supported by a conical concrete tower with several operation and auxiliary rooms inside it. The concrete tower, the azimuth rotating structure and the reflector rear side are protected against insolation and ice accumulation by an outside cladding.

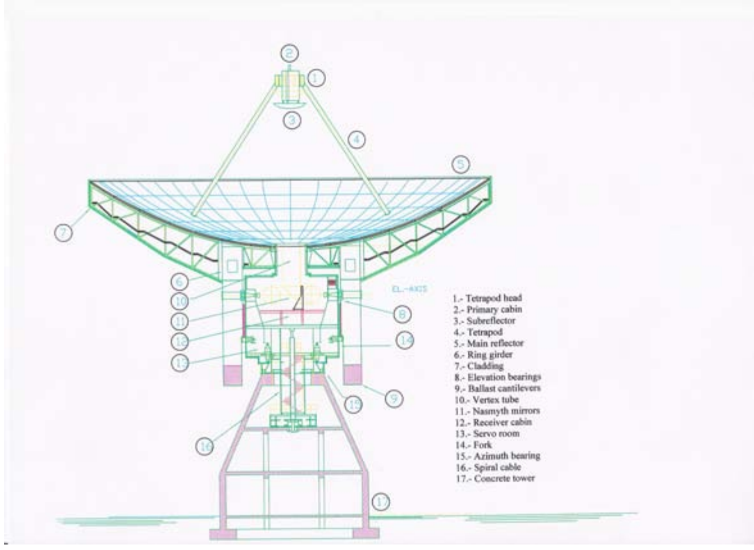

Figure 5: The IGN 40 meter radio telescope diagram.

All parts of the telescope are mainly welded together and fabricated with a high-grade accuracy that allows the welding to be done with a minimum distortion and to remain within the flatness and straightness tolerances and specified dimensions. The steel structure comprises the azimuth bearing supporting structure including apron and central tube bearing, the fork platform including the receiver cabin, the access facilities and the reflector trusswork including the tetrapod.

The fork consists of a platform of hollow box type welded steel construction and the two fork arms. The inner space of the platform is used as an operating room in which the azimuth and elevation drives are arranged. The access facilities comprise the central tube with the spiral staircase including the guidance at the anchor ring, the annular landing above the cable twister, the staircase between central fork room and upper level of the receiver cabin and all safety rails.

The main motion control system has a cascade three loop structure with trajectory generator, as is common in modern large steerable antennas. The trajectory generator prevents saturation non-linearities and provides smooth and fast settling in displacements between distant directions while the three nested loops (current/torque, velocity and position) increase the accuracy and stability of the system. The fact that the position and velocity loops are implemented by software allows for easy addition of feed-forward corrections, further increasing the accuracy for tracking radio sources.

Figure 6: One of the four azimuth drive assemblies of the 40 meter radio telescope.

The hardware elements of the main motion control, besides the control computer (ACU) are the servoamplifiers, encoders and drive assemblies.

The drive assembly, Figure 6, is composed of motors and reduction gears. Electric drive DC motors are used because they have excellent speed versus torque characteristics and can be controlled over a wide speed range. The reduction gear consist of a gear train normally based on planetary gear train. The reduction gears are accompanied by backslash. Precision antennas are provided with duplicate motors and reduction gears to which opposite bias torques are applied to reduce backslash. Each axis of the 40 meter radio telescope is equipped with four drives (motor and gearbox) working opposite in order to improve this backslash performance. The maximum speeds for the antenna are 3^o/s in azimuth and 1^o/s in elevation. The acceleration are $1^o/\mathrm{s}^2$ in azimuth and $0.3^o/\mathrm{s}^2$ in elevation.

Besides the motion in the main axes, the 40 meter radio telescope, like most high precision large telescopes, is fitted with servocontrolled movable subreflector. The purpose is to keep the subreflector aligned with the main reflector at any elevation by compensating for gravitational deformations of the overall structure.

5 The reflective surface

The reflective surface is made of a number of pie panels arranged in concentrical rows. The reflector panels can be of mainly two types: single skin or sandwich type panels. A single skin type consists of a thin aluminum plate, shaped to fit the required surface, with stiffeners attached to the rear side of the plate. The most common is the stretched-formed sheet. In this particular case the edges of the sheet are pulled over a curved mold. A Z section framework is then glued and riveted to the curved sheet metal. When the assembled panel is released from the tooling it acquires a parabolic shape.

Figure 7: Workbench for testing the 40 meter panels at different elevations using photogrammetry.

The single skin panel is lower in cost, but also comparatively low in stiffness. Very good surface accuracy is difficult to achieve (not better than 50 microns rms) because the production errors of the skin are added to the assembly error. This technology was used in the 40 meter radio telescope panels and the accuracy of most of the panels is below 65 microns rms.

A sandwich panel consists of a lightweight material with skins attached to the front and rear surfaces. The core usually is composed of a honeycomb or foam material, whereas the skin may be aluminum or metallized plastic such as glass fiber reinforced or carbon fiber reinforced plastic. This technology was used for the IRAM and ALMA radio telescopes [10], having better accuracy (near 20 micron rms), high stiffness and lightweight but more expensive manufacturing.

Surface accuracy of panels is tested using different technologies. The most common is direct measuring and comparison on a template by gauges, such as the sweep boom template measurement. New methods as the photogrammetry offers higher measurement accuracy and ease of measurement. Furthermore, this method allows the measurement at different environmental conditions (temperature, gravity, wind, etc.). This method was used for the characterization of the 40 meter panels, Figure 7.

6 Telescope construction

The telescope construction starts with the workshop assembly of the steel parts and the pedestal (the concrete tower) construction on site.

During the workshop phase some important assemblies need to be performed. First, the azimuth bearing should be integrated with its lower and upper supporting rings and its correct movement has to be checked. A common practice and a very important step is the trial assembly of the trusswork. All the truss members should be assembled in the workshop in order to verify that they fit before being sent to the site. Other trial assemblies for the azimuth fork, the cantilevers with the gear rims or the tetrapod are appropriate practices. Finally, the mounting of the elevation bearings with the journals and axle housings is then performed, previously the bearing clearance is adjusted.

Corrosion protection is an important issue for steel antennas and a high-quality anti-corrosion system involving several layers of prime and white paint based on zinc dust should be applied. The first coats are usually applied in the workshop, the last coat is applied on site during the erection.

The lower part of the receiver cabin must be bolted or welded on site on the azimuth fork, the upper part of the receiver cabin is then bolted on the lower part. The elevation bearings assemblies are mounted on the fork arms and the devices in the receiver cabin (e. g. doors, hatches, fan) shall be installed. Finally, the cabin shall be protected from atmospheric influences by an external cladding with insulation.

Prior to any lift, the azimuth cable twister shall be mounted completely including cable floor and grouting. Then, the azimuth bearing assembly, the spiral staircase and the azimuth fork (following this order) have to be lifted by means of big cranes on top of the pedestal. The central part of the fork platform will be connected to the azimuth bearing through a precisely machined contact surface. The complete assembly is then aligned by means of adjusting screws to the alignment specifications that are usually less than 10" and grouted to the concrete tower head with non-shrinking cement grout. The fastening screws must be loaded with a hydraulic device. The ballast cantilevers are then lifted and installed on the fork arms.

The reflector trusswork is assembled on the ground on the concrete foundations specially made for this assembly. This trusswork, consisting of main and intermediate trusses, ring girder and ring bracing, will arrive at the site in individual parts, which have to be welded together. The cladding, fans and electrical cabling should be installed on the ground also. Then the whole assembly has to be lifted, installed and welded on top of the cantilevers, Figure 8. After that, the tetrapod legs with the apex and the subreflector mirror can be lifted and bolted to the reflector trusswork.

The drives have to be mounted to the fork. After adjustment of the toothing clearance the gear box supports are pinned up. The gearboxes must be filled with oil, the gear rims have to be greased. The encoder supports, the actuating shafts, the motor driven locking devices, the limit switches and the auxiliary equipment must be mounted and adjusted. Finally, with the installation of the servo racks the antenna can be moved in both axis.

The reflecting panels can now be installed. The panels have to be connected to the supporting structure by means of special setting elements. With these supports the panels can be adjusted from the panel top side.

Once the construction phase is finished, the alignments and adjustment have to be done. First the balance can take place by pouring a mix of concrete and steel in the ballast arms. The elevation axis horizontal alignment has to be adjusted with the specified accuracy, normally close to 5", by means of a high precision level.

The reflector panels shall be set to the specified accuracy. This is usually done so as to obtain optimum alignment at 45^o elevation. Alignment of panels is made by means of adjusters and is a tedious task. Initially this is accomplished by rough alignment of the support clips of the backstructure with a tape measure stretched from a center theodolite station and setting them to an elevation angle. Final alignment is done by a mechanic who turns the adjuster following the instructions of the theodolite operator at the vertex of the parabola. Best fit data reduction of the theodolite angles yields angular changes needed to finish setting the reflector surface to the desired surface accuracy.

The final alignment is then performed using modern techniques of holography [11]. Microwave holography has proven to be a valuable technique for char-

Figure 8: Lifting the main reflector of the 40 meter IGN radio telescope.

acterizing the mechanical and RF performance of large reflector antennas. This technique utilizes the Fourier transform relation between the far-field radiation pattern and the aperture-field distribution. Resulting aperture phase and amplitude data can be used to characterize various performance parameters including panel alignment, panel shaping, subreflector position, antenna aperture illumination and gravity deformation effects.

The final commissioning of the servo system and the installation of the first receivers can then be accomplished. The first observations will check the real performance of the radio telescope.

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