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Commission B4 - IAU/URSI Working Group on Historic Radio Astronomy
The history of large single dish projects and lessons learned

Review of the evolution of large single dishes

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Slide 1 - Archimedes' Burning Mirror at Syracuse

1. Introduction

Here is a picture of a mural by Giulio Pangi (~1599) in the Galleria degli Uffizi in Florence with the title "Specchi Ustori di Archimede", in English, "Archimede's Burning Glasses". Most historians believe it never happened. If it did it was the first application of the focussing properties of the paraboloidal reflector; not for astronomy but for military action. You will already have noticed that the artist did not know about focus. The Suns' light concentrates on the mirror and is reflected in a divergent beam towards the ship. It would be hard to get anything burning! It is however interesting to note that for a successful attack the mirror would have been an offset paraboloid, a geometry that receives increasing interest from current radio telescope designers and users.

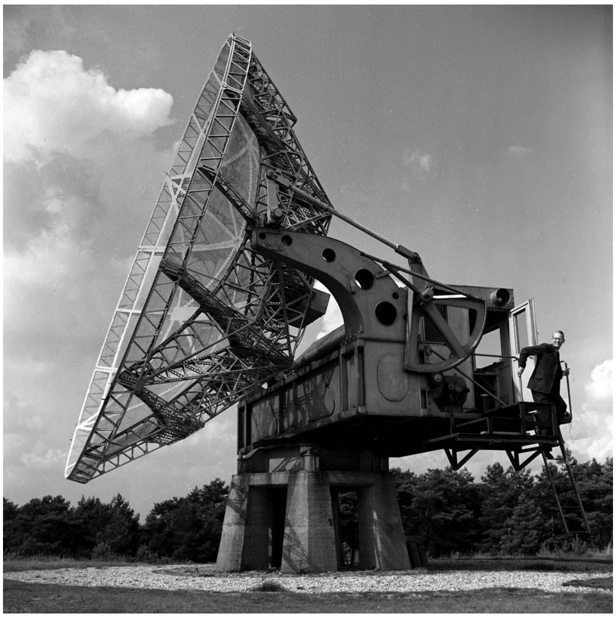
Slide 2. Reber with his dish at NRAO, Green Bank and ESO ELT model, both with “rocking chair” elevation drive.

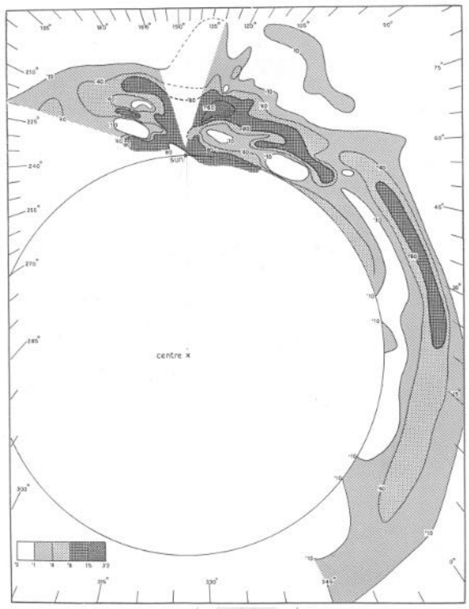
After Jansky detected radio radiation from the direction to the Galactic Center in 1932 at a wavelength of about 15 m, radio astronomy was started in earnest by Grote Reber, an engineer and radio Ham, not an astronomer. He single-handedly designed and built a parabolic reflector of 9.6 m diameter in his backyard in 1937. The reflector could be moved in elevation; the rotation of the earth provided for the azimuth movement. (Slide 2)
Reber worried about the precision of the reflector and aimed at maximum deviations of about 1 cm. He mistakenly thought that the signals would be stronger at shorter wavelengths. After starting at 10 cm wavelength he ended up at about 2 m, where finally he received measurable radiation. The design of the transit telescope is very original and modern. The “rocking chair” concept of the elevation structure and drive has hardly been used later for radio telescopes, but appears now in the very large optical telescopes, as for instance the ELT of ESO.

Here I review the major aspects in the development of the design and realisation of reflector radio telescopes over the last 70 years. I illustrate this by showing telescopes where original ideas or advances in material and fabrication were introduced. No details will be discussed. Later papers in this session will present those.

2. Early large telescopes

At the end of the second World War physicists and engineers emerged from the radar laboratories in England, Australia and the USA. Knowing about Reber’s work, and having experienced the influence of the Sun on their radar operation, they turned to do radio astronomy with the available radar equipment. In Europe tens of German radar antennas, placed along the coast, were left by the retreating German army. Quite a number of those were turned into radio telescopes. They were deep parabolic dishes of 7.5 m diameter and known by the German name “Würzburg Riese” - Giant of Würzburg, which illustrates the state of art at that time. A picture of the one in the Netherlands that detected the 21-cm spectral line of atomic hydrogen at 21 cm wavelength in 1951 is shown in Slide 3. The person on the stairs is Lex Muller, who built the receiver and operated the telescope during the discovery. The antenna originates with the aircraft manufacturer Zeppelin. The reflector consists of punched - hole aluminium sheets. The supporting lattice structure reminds one of aircraft stringers. The reflector is attached to the elevation bearings about halfway between center and ridge. A map of the Galactic HI distribution was a major result of the telescope.





Slide 3. “Würzburg Riese” 7.5.m radar antenna in Kootwijk detected 21 cm hydrogen line.
The observed map of Galactic hydrogen is shown on the right.

In the early fifties proposals emerged in Europe, Australia and somewhat later the USA, for radio telescopes in the form of large parabolic antennas. In the Netherlands Professor Jan Oort proposed a 20- 25 m diameter telescope for the observation of the 21 cm hydrogen line, even before the line was detected. After that event his proposal was quickly granted resulting in the 25 m Dwingeloo telescope becoming operational in 1956, the largest fully steerable telescope in the world. It was a first project by Ben Hooghoudt, who would contribute significantly to telescope design, both radio and optical, in the following decennia. (Slide 4)

The telescope uses the primary focus with a central mast supporting the detector. A truss-frame supports the reflector with a rather large f/D=0.5 that allows for flat triangular surface panels. The reflector is attached to the elevation bearings at about two-thirds of the radius. The alidade is a wheel-on-track system.

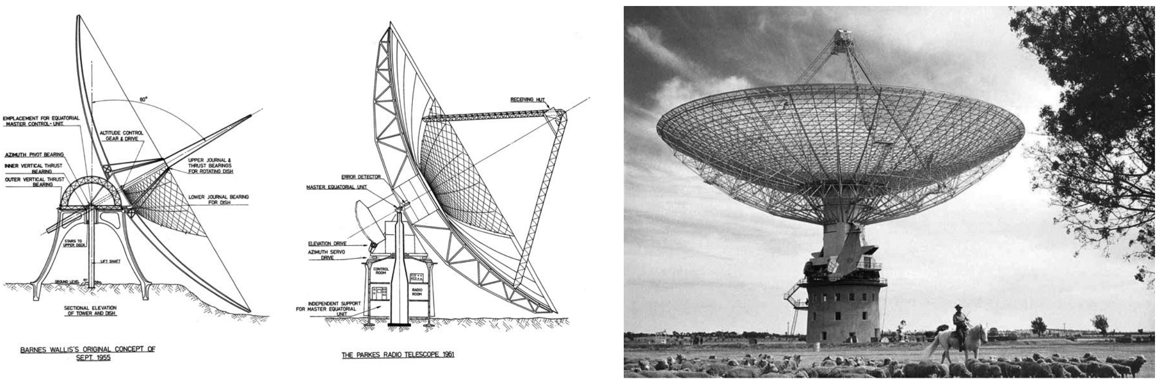
Slide 4. The 25 m Dwingeloo telescope in 1956 was for about a year the largest radio telescope in the world.

Concurrently Bernard Lovell at the university of Manchester obtained funding for the design of a 250 ft (76 m) diameter reflector to operate at 1 m wavelength. Bridge builder Charles Husband produced a design sketched in Slide 5 (left). It is immediately clear that this originates from a designer of bridges. After the detection of the 21 cm line, the requirement for the 250 ft was upgraded to a shortest wavelength of 20 cm. The mesh surface was replaced by a welded steel reflector that was part of the load bearing structure. A stiff outer hoop supports the deep bowl (f/D=0.25) and connect to the elevation drives. The final telescope at its completion in 1957 is shown in Slide 5 (right).

Slide 5. Jodrell Bank 250-ft telescope. First design sketch and realised MARK I in 1957.

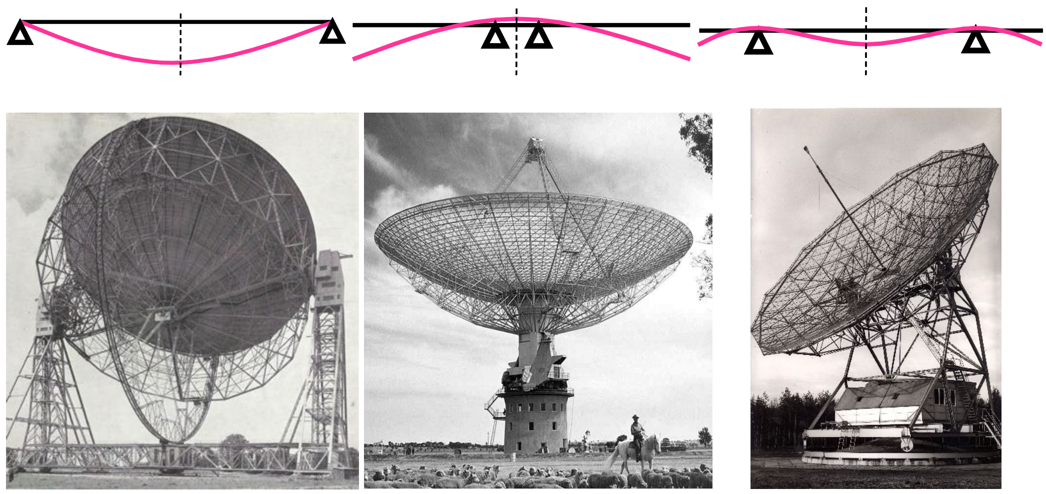
Around 1955 Taffy Bowen , head of CSIRO in Australia, made progress in his plan for a large telescope after contacting the British aircraft designer Barnes Wallis. Wallis produced a conceptual design that he believed could be used for reflectors up to 300 m! It became the basis for the 210 ft (64 m) telescope in Parkes. Slide 6 shows Wallis' concept and the final design drawing. The aircraft designer is apparent in the left sketch. The truss-frame reflector structure has a stiff central hub that connects to the elevation turret. The turret runs in azimuth on a compact track on top of a concrete support tower that limits the elevation coverage. The reflector has a mesh surface adequate for wavelengths upwards of 10 cm.

The telescope was completed in 1961 after an astonishingly short construction time of only two years. The German company MAN constructed and erected the telescope based on detailed designs by Freeman-Fox of England.



Slide 6. Parkes 64-m telescope in Australia. Original first proposal sketch (left), final design drawing (center) and the completed telescope in 1961.

Let us look a bit more into the structural aspects of these early telescopes. The three telescopes mentioned above use very different ways of connecting the reflector to the elevation bearings. This is illustrated in Slide 7.



Slide 7. The deformation pattern dependence on location of connection to elevate bearings.

The Jodrell Bank dish is supported by a stiff outer hoop structure and the hoop is connected to two elevation bearings at the top of the towers of the azimuth structure (gun turrets of a battleship). In the zenith position this causes a strong gravitational deformation in the centre of the dish; at low elevation an astigmatic deformation develops. Note that the “bicycle wheel” in the center does not carry loads; it stabilises the structure against wind gusts.

The truss frame of the Parkes reflector is connected to a very compact and stiff hub that connects to the elevation bearings. In the zenith there is strong deformation of the outer part; at lower elevation angles coma type deformations appears. A better solution is shown by the Dwingeloo telescope. Here the reflector structure is connected to the elevation bearings at about two thirds of the radius. Now the S-shaped deformation is considerably smaller in amplitude. Most later antennas apply this geometry of reflector connection. It is interesting to mention that the design of this telescope was guided by a “technical physicist” (as they were called in Holland) Ben Hooghoudt, neither a bridge builder nor an aircraft designer.

All three telescopes employ a alt-azimuth mounting. The coordinate transformation from celestial coordinates was realised by custom designed mechanical-optical devices providing an accuracy of about half an arc minute.

This is in sharp contrast to the situation in the USA. In the late fifties several telescopes were built in the USA, most of which used an equatorial mount. The 85 ft (26 m) Blaw-Knox antennas should be mentioned here for an original idea, proposed by Howard Tatel of the Carnegie DTM Institute. He used large diameter gears (Slide 8, left) for the axis drives that provide high precision for relatively low cost. The detailed design was carried out by Bob Hall, who was later pulled out of retirement to manage the construction of the GBT.

Slide 8. Equatorial mounts of the NRAO 85-tt “Howard Tatel” telescope (1959) with large gear-racks and the 140-ft (1965) with hydrostatic bearings and aluminium backup structure.

The ultimate polar mounted radio telescope is of course the Green Bank 140 ft (43 m) that was choke full of new ideas that were extremely costly and time consuming in design, construction and installation. The telescope took more than three times as long as planned and cost almost thee times the original contract. It came into operation in mid 1965 (Slide 8, right). One could easily devote a half hour talk to discuss all technical and managerial aspects of this project, but one can also summarise by noting that no large equatorially mounted radio telescope was later built in the US. It should also be remarked that the 140 ft, capable of observing at 2 cm wavelength and superbly operated with state of art equipment, became one of the most productive telescopes ever. That is typical for NRAO; another example is the 36 ft millimetre telescope on Kitt Peak.

Parallel to the 140 ft, MIT-Lincoln Lab built the 120 ft (36 m) Haystack antenna*, placed in a radome. No astronomer was involved in conceiving this military radar project and an alt-azimuth mount was selected. Heavy use was made of computers, in particular new finite element programs that enabled the design of a lightweight reflector. It also allowed to apply "bias rigging", whereby calculated offsets were introduced in the surface during setting in zenith position that resulted in a best-fitted surface at intermediate elevation angle. This has become the normal way of setting the initial surface. The antenna became operational in 1964 and was upgraded several times. It is still in operation, also for radio astronomy up to a frequency of about 100 GHz.*

The late sixties were dominated by the penetration into the short cm-wavelength regime and the application of aperture synthesis, in particular earth-rotation synthesis. The first arrays were the "one-mile" and "5 km" arrays in Cambridge, UK and the Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands, a 12 element array of 25 m antennas that became operational in 1970. Interestingly these antennas were polar mounted, which is not illogical in view of the long, up to 12 hours, observing time.

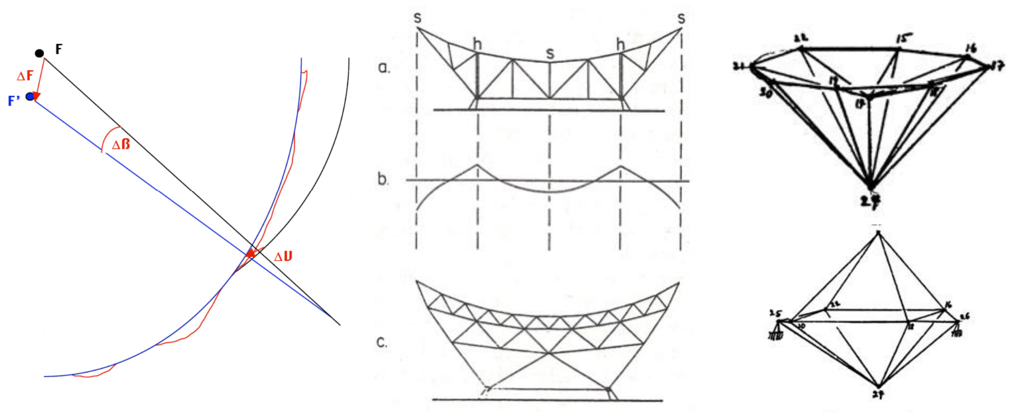
The WSRT antennas incorporate some novel aspects (Slide 9). Again, Ben Hooghoudt was instrumental in these original design aspects. The reflector structure is attached at four points to the declination cradle, not directly to the two declination bearings. This simple feature alone decreases gravitational deformation of the reflector by about an order of magnitude. For the first time extensive use was made of *epoxy resin*. The mesh surface was bonded to the panel frames and a pin-and-socket filled with epoxy served as a stress-free connection of the reflector with the structure of the declination cradle. After 6 years the mesh delaminated, but the pin-socket connection is still stable. Earth-rotation synthesis culminated in the completion of the VLA in 1980 with 27 alt-azimuth mounted 25 m antennas (Slide 9, right).

Slide 9 Aperture Synthesis in Cambridge (3X18m), Westerbork (12x25m), VLA (27x25m).

3. Homologous design - large and accurate telescopes

Several initiatives for a very large single dish with a diameter of the order of 100 m emerged in the late sixties. These would clearly need new design ideas and fabrication methods that would lead to financially realistic projects. A significant decrease in weight while maintaining reflector precision would be necessary. This was easier said than done. An unforeseen and happy circumstance led to a paradigm change in the design of large reflector antennas. A German theoretical astrophysicist and mathematician by the name of Sebastian von Hoerner spent the year 1962 as visiting scientist at NRAO in Green Bank. There he developed an interest in cosmology and the possibility of using lunar occultations of radio sources for obtaining accurate positions that were needed for optical identification. To obtain sufficient sensitivity he calculated to need a dish of 150-200 m diameter. When he saw the new 300 ft transit telescope, he felt that this must be possible. But “classical” designs based on providing stiffness would certainly be too expensive.

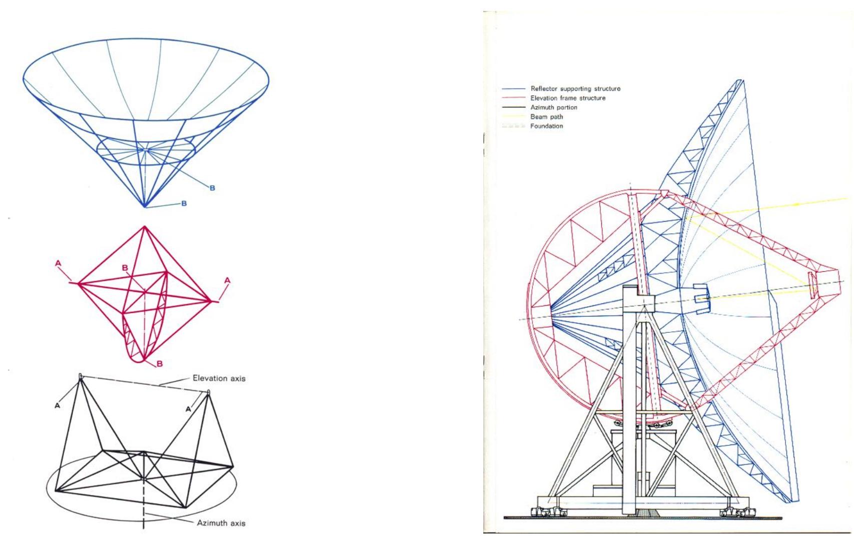
He then started from first principles and in a process, fully described in a fascinating article in the Astronomical Journal (not in a journal of structural mechanics!) in 1967, where he arrived at a design method for which he coined the name *homologous design* or shortly called *homology* (Slide 10). The principle idea is simple: design a structure that deforms with gravity in such a way that the best-fit reflector surface maintains a precise parabolic shape for all elevation angles, while allowing a change in focal length and axis direction (Slide 10, left). The surface support should exhibit “equal softness” to achieve small residual gravitational deformations (Slide 10, center). This could be realised by a symmetric support with an “umbrella” type structure to transfer the loads to the elevation structure. For the latter he proposed an octahedron consisting of the quadripod, a cone towards the elevation drive and the two elevation bearings (Slide 10, right).



Slide 10. Aspects of homologous design: principle, equal softness, octahedron, umbrella.

Von Hoerner showed that solutions for this task exist and produced the necessary algorithms for a practical design, including allowance for unavoidable tolerances in material properties and manufacturing inaccuracies. An optimum design would exhibit more than an order of magnitude smaller residual deformation error than a classical, stiffness based structure with a concomitant reduction in weight of about 50 percent. In his enthusiasm he concluded also a halving of the cost, but John Findlay reminded him of non-material costs like labour, transport and management.

More or less simultaneously Otto Hachenberg, director of the Bonn University Observatory, presented a proposal for an 80 m diameter high precision telescope. On the basis of deformation tests performed on an existing 30 m antenna he had noticed that best fitting, leaving focal length and axis direction free, produced a rather good paraboloid under changing gravity loading. Thus he instructed the design engineers into that direction. With newly available Finite Element Analysis (FEA) computer programs they produced a design for the Effelsberg telescope that shows all of von Hoerner’s basic solutions. (Slide 11)



Slide 11. The design of the Effelsberg 100-m telescope.

The main sections are:

i) the reflector with its backup lattice and cone-shaped ‘umbrella’ support (blue)

ii) the octahedron structure, including the elevation gear and the quadripod to the focus

iii) the alidade for the azimuth movement.

The Effelsberg telescope is the perfect demonstration of the power of homology design, even when von Hoerner’s algorithms were not applied for its design. With maximum absolute deformations of the order of 10 cm, its rms surface error is less than 0.5 mm. Its weight of 3200 tons is about equal to that of the 76 m Jodrell Bank, the 64 m Sardinia and the 50 m LMT. It is only 15 percent more massive than the NRAO 140 ft and weighs in at 40 percent of the GBT.

Slide 12. The 100-m Effelsberg Telescope.

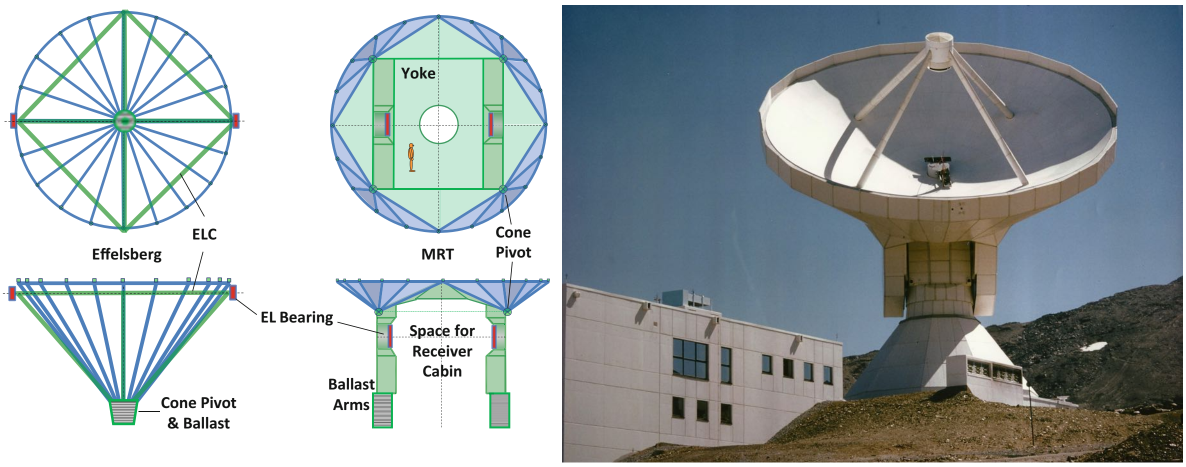
4. Millimeter telescopes - Improvements beyond homology

From the early 1970s onwards the principle of homology has guided in varying ways the design of radio telescopes. This is particularly significant in the realm of large mm-telescopes that were constructed in the following decades. In the mid-seventies major initiatives for large and highly precise mm-telescopes were started in the USA, Japan and Europe (Germany, France and the UK). Next to the application of homology, these necessitated the incorporation of control of wind and thermal influences on the behaviour of the telescope. Not only reflector precision of better than 100 μm needed to be realised; equally important was the accuracy and stability of the telescope’s pointing and tracking of the order of 1 arcsecond under operational conditions at the high and exposed sites.

A thorough treatment of the entire group of factors that influence the final performance was taken in the design of the 30 m diameter Millimeter Radio Telescope (MRT) initiated in 1975 by the MPIfR and carried out by the same industrial consortium of Krupp and MAN that had realised the Effelsberg antenna. The stated performance requirements translated to specifications for a 30 m diameter telescope with 100 µm surface precision, 1 arcsecond pointing and tracking, temperature uniformity of 1 Kelvin, all during day and night in 10 m/s windspeed. There was a further mundane but essential requirement. Because of the high altitude of the telescope and the still quite experimental character of the new types of cooled receivers, access to the frontends during telescope operation was placed high on the wish list of the future users and operators. This pointed to a spacious receiver cabin at the Cassegrain focus behind the dish or the use of a Nasmyth focus with the advantage of a receiver that remained stationary with elevation change of the telescope.

It became quickly clear that the superior umbrella support of the 100 m Effelsberg could not be accommodated in a 30 m diameter antenna while maintaining a spacious and accessible receiver cabin. Thus an alternative for the umbrella that would create a base for homologous behaviour of the reflector needed to be found.

The solution is an extension of the basic four-point support, as mentioned earlier. It is shown here next to the Effelsberg geometry in Slide 13.



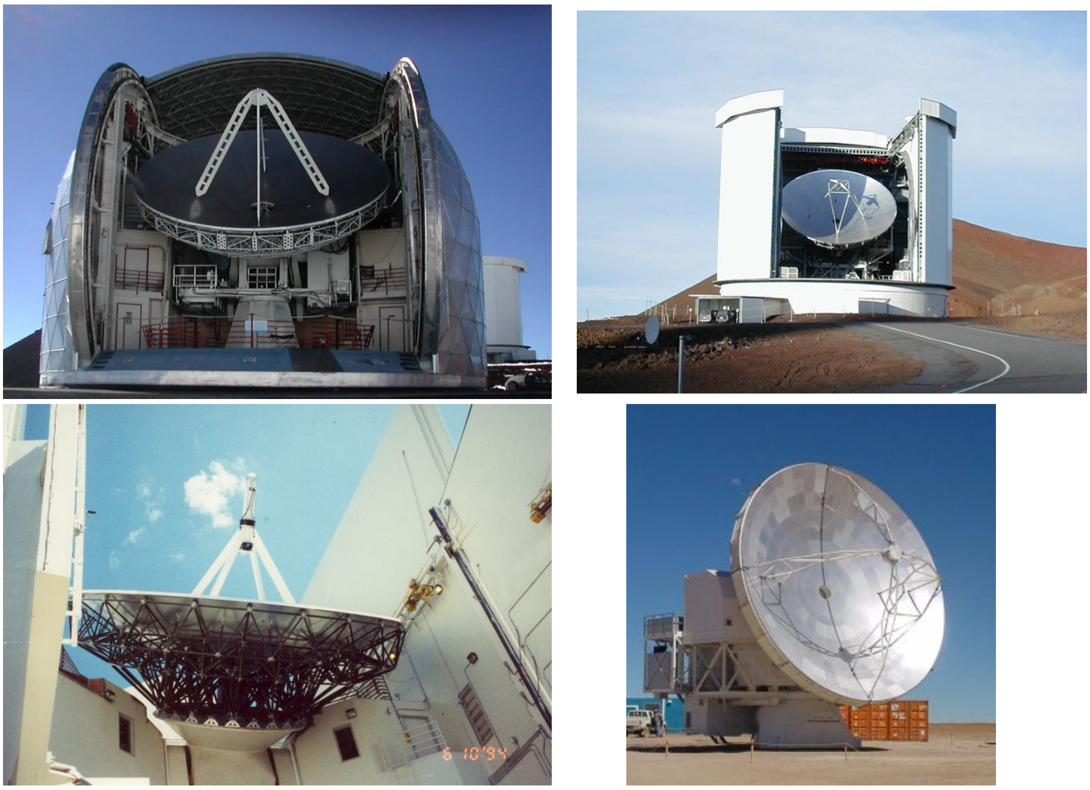
Slide 13. Homology design of the MRT compared to the original Effelsberg solution.
This creates space for a roomy Nasmyth focus cabin between the elevator bearings.

The octahedron was replaced by square yoke structure (green). The “cone pivots” were lifted to the corners of the yoke. From there a semi-conic structure of plates extended upwards and outwards to create a circular disc of 14 m diameter (blue). The homologous truss-frame of the BUS is supported at 20 points along the circumference of the disc, which remains flat with varying elevation and provides homologous behaviour of the elevation structure. The picture of the antenna shows that the azimuth movement is realised by a turret type “turning head” with a 5 m diameter roller bearing. This solution could be used because bearings with such a large diameter had just become available. Nowadays sizes of close to 10 m are available, notably for windmills. For the thermal control of the antenna an active system needed to be designed and installed. It is the most extensive system on any radio telescope and it maintains thermal equilibrium to about 1 kelvin.

5. CFRP and submillimeter wavelengths

The mm-telescopes of the 1980s show an increasing use of *carbon fibre reinforced plastic* (CFRP), first in the surface panels and subreflectors, for instance Nobeyama 45 m telescope and the MRT, later also in the support structure, as in the IRAM 15 m interferometer. Especially in the panel area there have been some problems, such as delimitation due to humidity penetration of insufficiently sealed panel edges.

Design and technology were challenged to realise telescopes that would function well at 1 THz, the truly submm telescopes. Around 1990 a few were built, notably the original 10 m “Leighton dish” and the 15 m JCMT, shown in Slide 14.



Slide 14. Submillimeter telescopes; from top left clockwise: CSO-10.4 m-Hawaii-1986, JCMT-15 m-Hawaii-1987, APEX-12 m-Chajnantor-2005, HHT-10 m-Arizona-1994.

For the CSO Leighton used the available turntable for the Palomar mirror grinding. The JCMT applied motorised panel adjusters, but they have not been used in an active system. The 10 m HHT of MPIfR employed a CFRP truss-frame with invar nodes and reached 12 μm overall surface precision with 6 µm CFRP-alu honeycomb panels realising a thermally highly inert telescope. It demonstrated that submm antennas of that size can be operated unprotected without active surface control.

Slide 15 Pictures of ALMA antennas on Chajnantor, Chile. Foreground: the 12 m diameter antennas from “North America” (left) and “Europe” (right) , 25 of each. Background: Japanese contribution of 12 m antenna (left, 4 off) and the “compact array” of 12 dishes of 7 m diameter.

The 12 m ALMA antennas all have CFRP backup structures and quadripods. The European ALMA antennas also use CFRP for the entire elevation and receiver cabin structure. Up to now no azimuth structure has been realised in CFRP, but thermal control is achieved with heavy insulation and often active regulation. These antennas have a surface precision of 20-25 µm and pointing stability of about 0.5 arcsecond in the “open air” at 5000 m.

5. Mechatronics - active optics

Parallel to the development of the relatively small submm antennas there have been a few large telescopes with extremely high performance specifications, notably the 50 m LMT in Mexico, the 100 m GBT of NRAO in Green Bank, the 65 m SRT in Sardinia and, just starting, the 110 m QTT antenna in Urumchi, China. Each exhibits some variation of standard mechanical design (Slide 16). All have a wheel-on-track azimuth mounting.

The 50-m LMT has a central concrete pedestal on top of which rests a pintle bearing that effectively absorbs the turning moments caused by the wind. The 105-m GBT uses an offset geometry for the reflector that avoids aperture blocking, but this has significant structural consequences leading to a weight 2.5 times that of the Effelsberg antenna. The 64-m SRT on Sardinia realises good homology with some variation on the “umbrella” concept. But these telescopes could not be realised in an economical way without incorporating real-time adjustments and corrections during operation. We are entering the domain of "*active optics*" in the current and future high precision telescopes.

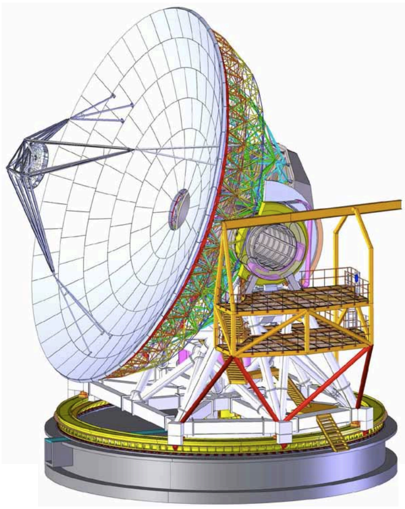
Slide 16. LMT-50 m-70 µm surface in Mexico; GBT-105 m-400 µm in the USA; SRT-64 m- 300 µm in Sardinia, Italy. All use tilt meters for pointing correction and thermal sensors for surface correction.

In these antennas, the surface panels of the reflector are connected to the BUS through motorised adjusters that must apply corrections to their position depending on the elevation angle of the telescope and also temperature variations in the support structure. These corrections are based on application of the detailed finite element model of the structure and achieve satisfactory results for these instruments. On the Effelsberg telescope the large-scale deformations in the primary reflector are corrected by an active subreflector that has almost one hundred of adjustable facets.

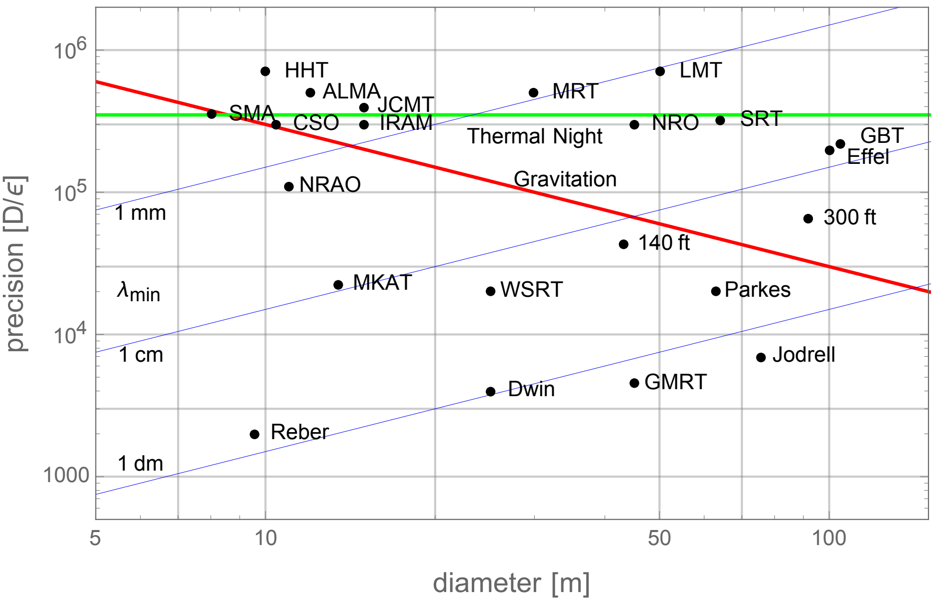
More difficult is the construction of a thermal model that must be based on a sufficiently dense network of temperature sensors within the structure. Operational wind normally does not significantly decrease the surface precision but plays a major role in the achievable pointing precision and stability. No properly functioning corrective pointing system has been implemented up to now. The field of *online metrology* is becoming an inherent part of the design and operation of the most accurate telescopes.

6. Conclusion

This is a session on the history of large single dishes, so I won't dwell on the future but for a few remarks. There are some initiatives for a "largest feasible" submm telescope, including the goal of observing at 1.5 THz in the hope that the atmosphere will allow it, which will become more unlikely with passing of time. And then there is the SKA with a huge collecting area divided over a few thousands of dishes 15 m in diameter. These will be offset antennas, useable to about 20 GHz. The challenge of the design is not in reaching the performance but in achieving a rock bottom unit price. A first prototype has recently been manufactured in China (Slide 17). It looks like a nice design, but it is too early to pass an overall judgment.



Slide 17. Design concept for a 25 m THz telescope (CCAT) - will be very expensive!
Picture of a first SKA dish prototype at the factory in China - must be dirt cheap!
A second SKA antenna is being installed in South Africa for MPIfR.



Slide 18. Radio telescopes on a"precision vs diameter" plot with von Hoerner's
"natural limits" gravity and thermal; blue lines indicate "minimum wavelength".

To conclude Slide 18 shows the well-known "precision versus diameter diagram" with the gravitational and thermal limits for "classical" designs together with the positions of some 20 telescopes in this area. Homology has brought an improvement of about an order of magnitude in the residual deformation (Effelsberg, MRT, NRO). To reach higher, active control is needed (GBT, LMT, SRT).

In closing I like to make the following remark. If you want to acquire a state of art telescope, you have to start with establishing a solid science case upon which the necessary telescope performance specification can be build. In early discussions with experts from industry translate these to achievable structural, mechanical and control specifications. Make those solid; don't start with including "goals"! Goals are expensive and remain uncertain. And be prepared to undertakes specialised tasks (control, metrology) in house. Having a core operational staff on site at the time the contractor starts acceptance testing will significantly speed up the acceptance and commissioning.

Further reading.

Book:
Radio Telescope Reflectors
Historical Development of Design and Construction

Authors: Jacob W.M. Baars and Hans J. Kärcher
Springer Astrophysics and Space Science Library 447 (2018)

Review Article:
Seventy years of radio telescope design and construction

Authors: Jacob W.M. Baars and Hans J Kärcher
URSI Radio Science Bulletin, No.362 (Sept 2017), pp. 15-38