NLSRT Memo No. 53

# REPORT of the TECHNICAL ASSESSMENT PANEL for the 300 foot RADIO TELESCOPE at GREEN BANK, WV

## SUMMARY


The 300 foot Radio Telescope at Green Bank, West Virginia which collapsed under its own weight while transiting on November 15, 1988 appears to have met and exceeded the original expectations of astronomers.

A post collapse finite element space frame stress analysis, under self weight only, indicated that the stresses in a large number of circumferential and radial members were substantially higher than those currently permitted - in some cases by as much as 100% and more. Although only one connection was reviewed, it can be extrapolated that many gusset plates were overstressed by "secondary" forces not considered in the original design.

The fractured gusset plate which was observed during an inspection of the wreckage, was reviewed and found to be a critical connection in the diamond truss.

It was found that the stresses were high and the stress range during telescope transits indicated a limited fatigue life. This was verified by the fractographic examination which indicated that fatigue crack propagation under cyclic loading resulted in eventual fracture of the plate.

The Technical Assessment Panel concludes that the fracture of this gusset plate connection is the most probable cause of the telescope collapse. From a review of Observatory records, the failure of the telescope structure was not a result of inadequate maintenance or inappropriate operation of the telescope.

The analysis methods used in this study were not available at the time the telescope was designed. The understanding of fatigue and crack propagation under cyclic load have greatly advanced since.

This collapse points dramatically to the importance of having an accurate and comprehensive stress analysis for this type of movable structure, which can identify fatigue and crack propagation susceptibility in critical elements in order to establish programs of inspection and subsequent strengthening, repair or replacement.

There are no unfavorable implications about the current ability to engineer future telescopes of this or larger size.

## 1. BACKGROUND

The 300 foot diameter Radio Telescope at Green Bank was designed and built over a period of two years and put into service in October, 1962. At the time of its construction, this telescope was conceived to be an interim facility which would satisfy certain immediate instrument needs not being satisfied as a result of delays and cancellations of other planned or projected instruments. A high priority was placed on minimum cost and expeditious construction. The minimal environmental requirements imposed on the designer support the conclusion that the telescope was not intended to be a permanent facility. The scientific usefulness extended many years beyond the expectations of the astronomy community as a result of the rapid advancement of detector technology which greatly improved the scientific yield. Since no other comparable United States instrument has been built, the machine never became obsolete.

Another factor which must be understood is a major improvement which has occurred in the design methodologies used by engineers working in the early 1960's as compared to engineers working today. This improvement, called **finite element space-frame stress analysis**, has been made practical by the advent of large capacity digital computers of widespread availability. This analysis method allows the structure being designed to be represented by a large number (e.g., thousands) of mesh points whose stress relationship is determined simultaneously whereas earlier methods required a complex structure to be simplified and typically neglected "secondary" flexural stresses due to frame distortions. Also, this antenna must be considered as a machine and as a dynamic structure, parts of which undergo large stress ranges in each transit of the structure. In this review, we used these modern methodologies not generally available to designers at that time. Our current understanding of the stresses of the structure thus greatly exceeds that available to the original designer, and our knowledge of fatigue and crack propagation due to cyclic loading is much improved.

## 2. HISTORY

The operators of the telescope, in routine visual inspection of the radial ribs and circumferential ring structure, observed and repaired occasional failures of smaller structural members from the very beginning of telescope operation. These failures were usually at the connection plates where structural members were joined by bolting. Over the 26 year life of the telescope, a few hundred such repairs were made, some in anticipation of failures in areas with high incidence histories. These repairs were never a detriment to the scientific performance of the instrument.

On a cool, windless night, on November 15, 1988, the telescope collapsed without warning while in transit motion. On November 18, 1988, senior officials of the National Science Foundation (NSF) and Associated Universities, Incorporated (AUI) established a Technical Assessment Panel to determine the cause of the telescope failure. On November 22, 1988, Panel members, E. Cohen and R. M. Matyas joined NSF and AUI officials together with a representative of the House of Representatives, Science, Space & Technology Committee and visited the Observatory at Green Bank. Interviews were conducted along with an examination of the wreckage.

A third Panel member, Dr. G. F. Mechlin, was added on November 28th. The first official meeting of the Technical Assessment Panel was held on December 9, 1988 in Washington, D.C. A key decision at this meeting was to order a finite element analysis of the telescope structure.

Another visit to the Observatory was made on January 4, 1989 by Dr. G. F. Mechlin and R. M. Matyas. During this visit and inspection of the telescope wreckage, there was observed a cracked major gusset plate connecting a lower element of the diamond truss which, at its other end, is connected to the bearing support framework. Based on a visual examination of the cracked surface, which suggested a significant crack which pre-existed the failure, one half of this cracked gusset was recovered and sent to a qualified metallurgical testing laboratory for examination. This laboratory examination is discussed in section 4 of this report since the gusset plate is believed to have played a significant or causative role in the telescope collapse. There are three other corresponding gusset plates in the structure. Two appear not to have a pre-existing crack. One (not yet recovered) exposed an indication of a pre-existing crack which appears significantly smaller than the crack on the plate already examined.

## 3. RESULTS OF THE FINITE ELEMENT STRESS ANALYSIS

The full report of this finite element analysis is provided as Appendix A. The salient findings of this analysis are that 1.) certain lower chord gusset plate connections of the diamond truss underwent numerous cycles of severe stress and 2.) the radial rib and circumferential ring structure in the vicinity of the trunion truss bearing support structure operated at stress levels at which buckling and plastic deformation would be expected to take place. Two consequences of resulting deformations are predictable. First, it would cause a redistribution of loads into other adjacent members, which would generally cause loads of these members to increase even beyond the levels calculated by our stress analysis. The second consequence would be the occasional failure of individual structural elements as observed. A design analysis performed four years after completion indicated some such overloaded elements. Some remedial repairs were undertaken accompanied by additional modifications to stiffen the structure and to improve the image stability.

It must be understood that the current analysis was made of the telescope in its idealized dimensional state prior to the collapse. Such a state is never achieved since stresses developed in a partially completed state during erection impose initial deformations and stresses which vary from ideal, which then would be additionally altered by the modifications and repairs mentioned above. As earlier suggested, these effects tend to make actual stresses greater than calculated for the ideal structure.

One concludes from the current analysis that, from the beginning of its life, the structure was marginal with respect to structural failures of a minor or perhaps a major nature. A very significant portion of this marginal status was that the diamond truss structure depended for stability on the interactive support of the radial ribs and circumferential rings which, in turn, contained members required to operate beyond their safe load carrying limit.

Because of complex load redistribution effects, one does not expect a strict correlation between individual members determined to be overloaded and observed individual failures. There is, however, a general correspondence between areas showing calculated overload and observed damage. Early in its life there were several significant modifications made to the telescope. These included the reinforcement and stiffening already alluded to. A new feed structure consisting of a dish-mounted, guyed bipod was added and the original open mesh dish surface was replaced with a finer mesh surface suitable for higher radio frequency operation. The finite element analysis reported herein found that after these modifications, the structural integrity of the directly affected portions of the telescope were somewhat enhanced.

## 4. SEQUENCE OF FAILURE

The Technical Assessment Panel concludes that the probable cause of telescope collapse was the progressive cracking of the gusset plate at the end of the lower chord of the diamond truss at the northeast corner. This lower chord at its other end intersected with the support bearing structure. The failure of the lower chord of the diamond truss in this location destroys the ability of the truss to carry load as a truss and collapse ensues. The progressive cracking was caused by excessive stress in the gusset. As calculated in the idealized state of the structure, the stress was far beyond limits which would have precluded such progressive cracking. The crack origin was probably associated with two punched bolt holes where the severe working produced by the punch could have left an initiating small crack.

The report on the metallurgical examination is included as Appendix B. Results of the metallurgical investigation of the fractured gusset plate revealed that the plate failed as a result of progressive cracking in the nature of fatigue. Propagation of these fatigue cracks under cyclic loading from both bolt holes eventually resulted in a fast ductile fracture when the combination of cyclic stress range and crack size exceeded the fracture toughness of the plate material.

The results of the fractographic examination revealed secondary fatigue cracks also had originated at the bolt hole surfaces. The presence of secondary fatigue cracks at the bolt holes indicates the presence of intermediate to high cyclic stresses.

It cannot be unambiguously determined whether the subject progressive crack had simply grown to a point where the remaining material in the gusset could no longer support the load or whether some otherwise minor event or failure immediately preceding the collapse added a new increment of load to the gusset. Two such minor events can be postulated. One event might have arisen from an increased friction force or jamming of a support bearing. The west bearing assembly was recovered for inspection while the east bearing is still inaccessible. During this salvage operation, the unloaded shaft was rotated with ease but when the bearing case was opened, the grease was observed to contain a myriad of metal flakes and the spherical rollers exhibited a peened surface demonstrating progressive damage. The appearance of the bearing rollers suggest only a modest increase in frictional torque, however, the bearing was in the initial stages of failure and probably would have itself prevented use or caused structural failure of the telescope at some future time. Another likely event is one or several failures of already overstressed radial rib or circumferential ring members shifting additional load onto the box frame truss.

The panel sees no merit in terms of lessons for the future in further tedious and perhaps impossible tasks of determining whether the gusset failed first or was driven to failure by such a preceding event. It is very clear that this gusset was rapidly approaching failure prior to the event and that the failure of this plate was the key element in the total collapse of the telescope.

The Panel recommends two additional corroborating investigations be performed by the Observatory as appropriate prior to or during wrecking. One is the recovery and visual examination (only) of the second gusset believed to be cracked. The second is disassembly and visual examination of the east bearing assembly for signs of distress which might indicate high friction or jamming.

The Panel further recommends caution and extreme care in recovering any artifacts or structural elements from the wreckage. In such activities as well as the subsequent disassembly and removal of the wreckage, it is imperative that the work be supervised and monitored by a competent structural engineer working with an experienced industrial wrecking crew.

## 5. RESPONSIBILITY

From a review of the records, it is the opinion of the Technical Assessment Panel that the failure of the telescope structure was not a result of inadequate maintenance or inappropriate operation of the telescope.

The contributory roles of the designer, the constructor or of the subsequent reviewer cannot be sensibly commented upon after so long an interval other than to say that the telescope performed longer than the expectations which the observatory and the designers must have shared.

There were no observed structural failures in the history of the telescope which would have suggested a need for a third engineering analysis of the sort performed in this investigation. The gusset plate in question was cracked in a fashion such that most of the crack was concealed beneath the structural elements to which it was connected. There was lacking any signal that the gusset was failing and an examination was not possible without disassembly, which could not be performed.

## 6. RELATION TO OTHER RADIO TELESCOPES

The Review Panel sees no direct implication from the failure of the 300 foot telescope to other radio telescopes. There were no phenomena observed in the operation of this telescope that could not be dealt with using modern design practice. It does point very dramatically to the importance of having an accurate stress analysis which would identify critical elements, crack propagation susceptibility, and required frequency of inspection, replacement, strengthening or repair.

The other, relatively minor, structural failures observed in the radial ribs and circumferential rings were detected through periodic inspection and repair. How these repairs contributed over the years to stress increases in the diamond truss gusset plates cannot readily or unambiguously be determined even with today's best state-of-the-art in stress analysis.

It should be understood by all telescope operators that their instruments are more akin to moving machines than to static buildings. Inspection and maintenance plans based on adequate knowledge of structural loads and service environment are a normal requirement of this or any other kind of machinery which the owners wish to keep in service.

It should be a requirement for the designer to identify from his design analysis, places and times where inspection for "fatigue type" progressive cracking should be made. Further, limited life components such as seals, hydraulic components and bearings should be identified and provision made for their inspection and/or replacement.

There are no unfavorable implications about the present ability of engineering science to design and build telescopes of this or larger size.