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Structural Design of the 45 m Diameter Antennas of the GMRT, Specifications, Summary of Analysis made by TCE, Safety Considerations and some Suggestions for the Proposed Review by TCE.

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(the draft report dated 02 06 -09 has been updated by adding comments by Shri Tapde, formerly Project Engineer, GMRT, Shri Yogi, formerly structural design engineer of TCE and of Dr. Gomathinayagam formerly of of SERC, CSIR, regarding "Basic Wind Velocity" at Pune).

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Govind Swarup-02 06 09

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1 Summary

This report firstly summarizes the structural design of the 45 m diameter parabolic dishes of the GMRT made by M/s Tata consulting Engineers (TCE) during 1988-89, highlighting four major design assumptions and then makes certain suggestions for the proposed review by TCE. The specifications and assumptions were made by TCE in consultation with NCRA-TIFR, some of which should be re-examined, as discussed in this Report, particularly loads at the focus, implications of somewhat higher survival wind velocity than assumed in 1988-1989, drag factors of the wire mesh and consideration of the maximum allowable stresses in the structural members by the wind and dead loads. I also describe some other aspects briefly, such as engineering design notes by TCE, displacement of the elevation axis with respect to the azimuth axis, rms errors of the surface, gravity deflections, safety considerations, **automatic stow locking of the 45m dishes** etc. Mechanical design of the GMRT antennas will be summarized in another report. This Summary is rather long as many astronomers and engineers may not wish to pursue the entire report and may find the Summary useful.

The following 4 major assumptions and specifications were made for the engineering design of the 45m dishes:

(a) Diameter: 45m, focal length/diameter ratio = 0.412 (focal distance 18.540 m). During 1988-89 when primary antenna feeds to be placed near the focus of the dishes were still being designed by the NCRA engineers, I specified their total weight as 250 kg (including supporting structures) and surface area of ~ 2 sq. m for consideration of the wind loads. In the computer analysis made by TCE, (i) a load of 1300 kg was assumed as the weight of the feed drive system, feeds and attachment of feeds to the feed cage, (ii) total wind load was assumed to be 2000 kg and (iii) moment of 42000 kg cm. I have recently searched the TCE documents of 1989 and 1990 available at NCRA but I am not able to find a listing of separate loads for different items placed near the focus. A possible lower total actual load will minimize **stresses** in the quadripod and also the ~8 cm displacement of the top of the quadripod with respect to the axis of the parabolic dish with its rotation from zenith to 17^0 elevation due to gravitational deflection, as calculated by TCE using a computer analysis.

(b) In 1988, the wind velocity of 50 kmph (3 second gust) was assumed for the ‘operational limit’ for rotation of the 45m dishes for astronomical and other observations. At a higher wind velocity, antennas are required to be rotated and stow locked automatically at the zenith position before the wind velocity reaches 85 kmph (i.e. within about 6 minutes, ~ 4 minutes for elevation rotation by 80^0 and ~ 2 minutes for any overheads before the stow locking command is issued to the servo system). Survival wind velocity of 133 kmph (37 m/s) was assumed for a 50 year return period at 10 m height (it may be noted that a 50 year return period specifies 63% probability of the wind reaching that velocity in 50 years and does not imply that the GMRT antennas will be safe for 50 years with a lower risk factor and if required, structures have to be designed for a higher wind velocity as discussed in Annexure A2). Terrain factors and increase in the wind velocity with height were taken as specified in the IS:875 Part III code (1987) of the Indian Standard Institute (ISI). However, recent data for the Lohagaon airport region in Pune indicates that there is a finite probability for the occurrence of the peak wind velocity of even 148 kmph in 50 years during the summer thunderstorms and squalls. Its implication to the GMRT needs investigations.

(c) The reflecting surface of the 45m dishes consists of, sparse, stainless steel welded wire mesh, made of 0.55mm wires, with mesh sizes = 10 mm x 10 mm, 15 mm x 15 mm and 20 mm x 20 mm for the inner, middle and outer parts of the dishes respectively. The wind drag factor, Cd, was assumed by TCE as 1.42 in the normal direction of the reflecting surface of the 45m dishes, at 40^0 ~ 0.8 and at 10^0 ~ 0.53. Recent data indicates that wind drag factors for the GMRT mesh may be lower by ~ 30%, as discussed in this Report.

(d) Value of the maximum allowable stress was determined based on IS-800-1984 code, being 0.60 of the yield strength, fy, for the axial tension, ~0.66 fy for bending moment, 0.66fy in compression, 0.75fy in bearing, 0.45fy in shear with equivalent stress < 0.9fy in the structural members of the 45m dishes. The stresses in the structural members of a parabolic dish due to the wind loads are likely to be appreciably smaller when the dish is pointed towards the zenith than other positions. *TIFR advised that the electrical drive system would be suitably designed in order to automatically stow lock the 45m dishes when wind velocity increases beyond 50 kmph (3 second gust).* TIFR suggested that since the probability of antennas **not** being stow locked was likely to be small, for other positions of the GMRT 45m dishes clause 3.2.2.1 of IS-800-1984 could be considered: "when the effect of wind or earthquake is taken into account, the permissible stresses may be exceeded by 33 1/3 % stresses". However, in the Detailed Design Engineering Note of 1989, DDEN-5 (v-05) by TCE, (page 3, item 2) it is stated that no permissible stresses is allowed for wind loads vide Para 3.9.4 of IS-800-1984 but equivalent stress can be 0.90fy as per column 3 of DDEN-5. From my quick Google search, it seems that the increase of 33.1/3% for wind load is not included in the revised draft IS-800 (2008). It would be useful to get clarifications regarding maximum stresses for the zenith and other positions in the new analysis being done by TCE.

I understand that automatic stow locking of the antennas in case of power failures, particularly during a severe thunderstorm and high winds in the summer months, has not yet been implemented at the GMRT. Appropriate actions need to be carried with urgency during the next 6 months well before the next summer months when squalls occur. I have suggested its importance several times over the last 15 years. It should not be delayed any further. I understand that diesel generators have been installed so far only at 6 out of 16 Y-array antennas. The diesel generators should be installed at the other 10 antennas with urgency. Also a suitable reliable circuit, as discussed in Section 6, needs to be developed for the automatic stow locking.

Shielding by the windward members of the triangular shaped trusses: The structural members of the quadripod, parabolic frames, rim and hub of the 45m dishes consist of triangular shaped trusses made of round tubes. For analyzing wind forces on the structural members of the dish, TCE firstly calculated wind forces on the **total** projected area of all the members of the triangular trusses but then applied 'overall force reduction factors' = 0.78 in order to account for the shielding effects by the front members of the trusses to other members of the antenna structure for the horizon orientation and 0.68 for the zenith case (ISI documents do not provide any guidelines for parabolic dish antennas). Analysis using Computational Fluid Dynamics (CFD) may provide more accurate values. Software for CFD is available at many private firms and also at CDAC and I2IT.

Joint rigidity: TCE made computer analysis of the stresses and deflections in the dish structures assuming pin-joints, but since the structural members of the GMRT antennas are all welded, TCE multiplied the pin-joint determined stresses by the 'stress increase factors' for the joint-rigidity varying from ~ 1.2 and 1.25 for the main members and 1.3 to 1.6 for the bracings and struts. A later analysis called RIGIDISH assuming clamped-clamped joints indicates that the assumed joint rigidity factors may have been over-estimated and this aspect needs a fresh look based on IS and international codes or practices for tubular welded structures.

Computer analysis: The structural design for the 45 m dishes was carried out by TCE during 1988 and 1989, based on eleven "Detailed Engineering Design Notes (DDE Notes)". Several design reports were discussed in detail with the GMRT scientists and engineers and suitable decisions taken. TCE developed several special computer programmes, and using them made an excellent and exhaustive analysis. Contracts were awarded for the construction of the antennas by the end of 1989. A report giving design basis for the 45m dishes and 8 computer outputs based on the pin-jointed space frame and stress increase factors was finalized as TCE.G18/DR/CAL/153-DISHCRAD dated 18 Feb 1990. Another report based on rigid space frame, called TCE.G18/DR/CAL/153-RIGIDISH, was released on 23 and 28 April 90. I may stress that only the DISHCRAD analysis has been used for the design of the 45m dishes. Seven other reports discussing various aspects of the structures of the 45m dishes and RCC tower were also finalized by TCE as listed in Annexure A5 in this Report. Papers by Janardan, Yogi and Swarup (1990) and Janardan, Yogi, Swarup and Tapde (1991) summarize design assumptions and procedures adopted for the analysis of the 45 m dishes.

Lists of (a) 10 drawings used for computer analysis and (b) 129 drawings for fabrication and erection are also included in this Report.

RMS errors: RMS surface error were specified as 12mm, 6mm and 4mm for *the plane wire mesh facets* for the outer, middle and inner 1/3rd area; and 24mm, 12mm and 8mm including displacements by dead load, and wind load of ~ 20 kmph, and fabrication errors. As described later in this report, distortion o f the paraboloid with rotation and wind loads is relatively negligible (~ 4mm) due to the selected 4 point stiff support of the hub. However, the fabrication errors are large particularly for several antennas. These could be corrected in principle today or tomorrow. Also one may consider using 6mm x 6mm x 0.55mm mesh for the inner 1/3rd area as its replacement can be done within a month with about 12 or 15 workers for each antenna 6 workers working on two opposite sides. This would cut down contribution by the ground temperature due to the leakage of the wire mesh at 21cm.

Review by TCE: NCRA has recently requested TCE to make a review of the structural and mechanical aspects of the 45 m dishes. NCRA has also asked TCE to review and advice permissible loads near the focal point of the dish as new antenna feeds are being developed. In addition to the structural analysis of the legs of the quadripod, TCE may also compute its natural frequency and dynamic loads. TCE is also looking into certain wear and tear and maintenance aspects. *It would be important to take a fresh look at the safety of the GMRT antennas at assumed survival winds*. Although the GMRT staff and TCE engineers would certainly look at all these aspects carefully, being closely associated with the initial design of the 45m dishes, I have taken the liberty to make some suggestions in this report that may be considered, *but these should not give rise to a bias.*

Basis for selection of certain design specifications: Although a bit repetitive, I discuss here basis for the selection of the four major design specifications, giving reference to various documents that determined their choice. **I also discuss in this Report the need to review some of the design parameters such as wind loads, considering recently available data. A brief discussion is given here in the Summary and further details are given in the Report:**

(a). *Load near the focus*: Apart from a review of the maximum allowable load at the focus, wind load on the surface area of antenna feeds, electronic units, drive system and their supporting structure would be determined. *The natural frequency of the quadripod needs to be calculated and its safety may be analyzed at survival winds (consideration of natural frequency of the quadripod alone was not done as per my recollections in 1988-89).* Recommendation given in IS875 for the dynamic effects need to be reviewed and an appropriate analysis for the quadripod may be considered. Safety aspects of the quadripod must be reviewed carefully, as in my view, the probability of its failure in case of very high winds should be small as its failure may cause major damage to other parts of the dish. Steel structures mostly do not fail suddenly. it would be prudent if a suitable monitoring scheme can be conceived that detects any large displacement of the quadripod, e.g. a small laser or led with a lens placed at the top of one of the legs of the quadripod aimed at a photodiode near the apex that may detect, say > 20 arcmin displacement of the quadripod.

(b). *Maximum Allowable Stress*: Stresses may be determined for the survival wind velocity of not only 37 m/s (133 kmph) that was assumed during 1989 but also for the 39 m/s (140 kmph) and 41 m/s (148 kmph). Any joints with a higher value compared to the maximum allowable stress, may be identified for the cases of these higher winds and commented upon, even if correction may not be practical. Such joints with > 0.8fy at the above mentioned high winds could be marked by a red paint so that such joints could be readily inspected, in case of the occurrence of the rare extreme wind.

(c). *Wind drag factor*: Wind drag factor, Cd, of the wiremesh was assumed as 1.42 in 1988 based on then available data. Considering recently available data as discussed in Section 4, I recommend a value of Cd of 1.2 at $\theta = 0^0$ for 10mm x 10 mm x 0.55 mm mesh, 1.1 for the

15mm x 15mm x 0.55mm mesh and 1.0 for the 20mm x 20mm x 0.55mm mesh in the inner one third, middle and outer portions of the GMRT respectively, decreasing as $\cos^2 \theta$ up to ~ 0.2 at 73^0 and remaining 0.2 up to 90^0. This change in specifications will result in somewhat lower stresses (perhaps by 5 to 7%) in the structural members of the 45m dishes at the assumed survival wind velocity of 133 kmph, and thus antennas becoming safe even for a higher wind velocity.

(d). *Shielding effects*: Shielding effects by the windward members to the backside members of the trusses of the parabolic frames, rims and the quadripod of the antenna structure, particularly for the zenith case assumed by TCE as 0.68 may be reviewed ,if practical, using Computer Fluid Dynamics (CFD) analysis, that may be practical now-a-days.

(e). *Joint rigidity*: During 1988 and 1989, TCE considered pin-jointed frame for the computer analysis of the GMRT antenna structures. Since the tubes of the GMRT are all welded, stresses calculated for a pin jointed frame were multiplied by estimated "stress increase factor". As discussed in Section 5, a brief comparison has been made by me recently of the 'total stress ratio' for various structural members of the 45m dish as listed in the computer outputs of the DISHCRAD and RIGIDDISH. I find that the stresses are about 5% to 15% lower in the main members of the triangular trusses of the quadripod, prfs, and rim; and ~ 30% lower for the struts and bracings of these trusses for the RIGIDISH computer outputs than for the DISHCRAD computer outputs. This may indicate that the actual stresses in the structural members at the survival wind would be appreciably lower than that given in the DISHCRAD outputs in case the RIGIDISH analysis is considered to take care of the rigidity of joints during the TCE review. However, this aspect needs to be discussed with Shri Yogi and others.

(f) *Proposed review, general comments*: During 1989 and 1990, TCE had considered wind load for the front wind and side wind at different orientations (perpendicular and parallel to the elevation axis). For checking stresses in the quadripod, in my view, it is also desirable to consider wind at 45 degrees, since in that case only the outer 2 of the 4 legs would have maximum stress due to the wind load. Further, I suggest that stresses (as a fraction of the yield strength) in the main structural members and bracings for the zenith case and other orientations may be presented or summarized *in separate tables*, in order to make it easier for appraisal by the GMRT scientists and engineers, at present and in future. The proposed analysis by TCE using STAADS programme allows graphical presentations. In the 1989 and 1990 computer analysis made in 1989 and early 1990, values for stresses are all mixed up and took me a long time to comprehend an overall picture (e.g. see computer outputs of DISHCRAD dated 18-Feb-1990 and RIGIDDISH dated 23 and 28-April-1990).

(g). *Mechanical drive system*: There are other aspects, such as review of stresses on the pins of the Bull gear, in case the antennas do not get stow locked (what is the maximum wind velocity that the pins will resist wind forces, assuming pinion of only one of the two gear boxes is in contact in view of the back lash and also the pinion may not be centered in the channel of the bull gear; **also required brake capacity of motors and their periodic measurements**, (h). *Grounding system of antenna structure*: At the top of the quadripod is located lightening arrestors. The steel structures are expected to conduct currents during the lightening strike. Further, there is 'grounding system' of the structure above the rotating slew-bearing ring that connects to an **earthing system that may need a review.** Its annual check-up is being done by conductivity measurements before the summer months to ensure that no damage occurs to the concrete tower and foundation if a severe lightening strikes one of the antennas; (past cases of any failures of electronics in the case of any lightning strike may be documented by the GMRT engineers). **I am sure** that many of the above items are being looked into by the GMRT engineers carefully as part of their systematic maintenance procedure but I have listed them here in order to highlight those aspects that affect the safety of the GMRT antennas. A check and countercheck system may be required, if not already there.

*(i). Automatic Stowlocking****: I hardly need to emphasize that the 45m dishes are like family jewels of NCRA, and in-fact of the nation.*** Their safety during the occurrence of the summer thunderstorm squalls with very heavy winds is most important, for which stowlocking minimizes any risk. In the case of failure or shutdown of the MSEB power to some of the Y-array antennas, particularly during the occurrence of thunderstorm, lightening and squall with high winds, communication from the control room to Y array antennas will also get disrupted. I understand that antennas are stowlocked at present by the telescope observers (operators), if the wind velocity averaged over 1 minute exceeds 45 kmph in the wind metre that is mounted at the top of the water tank in the Central Electronics Building (as per private communication by NVN on 090509). Even if the telemetry system is backed by UPS, stowlocking **should be made automatic at each antenna,** based on the wind velocity measured by the cup anemometers at each antenna **exceeding** 50 kmph, averaged over a minute, and further using diesel generators in the case of power failure. It is known that the wind velocity becomes very high, often in less than 10 minutes, during the summer thunderstorms and squalls.

I was surprised to know recently that (i) diesel generators have been installed at only 6 of the 16 Y-array antennas and (ii) only 15 out of the 60 wind meters are operational at present. **This situation needs to be corrected with urgency before the end of this year** (we are lucky that very high winds say > 130 kmph have not occurred at the GMRT antennas during the last 15 years).

The wind meters are located on the rims of the 45m dishes in the direction of elevation bearing at a height of ~ 20 m, whence the wind speed is expected to be ~ 1.07 times than that at 10 m height. Hence, we may revise the start of the stowlocking if the 1 minute average exceeds 50 kmph (gust of ~ 55 kmph). This would also minimize stowlocking during monsoon period from mid-June to end August when no squalls are expected. A barometer in the control room may be useful.

2 Introduction

A design breakthrough for the reflecting surface of the 45m dishes of the GMRT was made by the TIFR (Swarup 1986), using a SMART concept (starched mesh attached to rope trusses). It consisted of using sparse wiremesh of low solidity, supported by a set of stretched rope trusses connected to sixteen parabolic frames, in order to provide curved surface of the parabolic dishes, within the specified rms errors to ensure operation up to 1420 MHz. This concept minimized wind loading on the antennas, resulting in considerably economy. A report by Janardan, Yogi and present author (1991) summarizes the procedure considered by TCE for the design of the GMRT antennas. In addition eleven reports, "Detailed Engineering Design Notes" give exhaustive notes on the design and analysis of the structural parts of the GMRT antennas. Results of the computer analysis by TCE for the GMRT dishes are given in document DISHCRD dated 18 February 1990 and 8 other documents.

I discuss in this Report basis for selection of the four main design specifications that have been listed in the Summary. Specification (a) concerns loads near the focus that were based on scientific requirements and is discussed further in Section 2 of this Report. In Section 3 is discussed the design specification (b) that gives maximum value of the 3-second-peak gust velocity at the GMRT site likely to take place during the expected life of the GMRT, the so called survival wind velocity; it also describes the basis for selection of this specification. In Section 4, I discuss the basis for the selection made of the drag factor value, Cd, of the wiremesh of the reflecting surface of the dishes and the need for its revision, considering recently available data.

Section 5 describes the final computer analysis of the 45 m dishes made by TCE in 1989 and the maximum allowable stresses in the structural members. The maximum values of stresses in the structural members were based on IS800-1984 code. Initially TIFR, suggested that maximum value of the allowable stress as ~65% of the yield strength, fy, of the structural members in the stowlocked zenith position of the 45m dishes to ensure their safety when subjected to the specified "survival wind velocity" of 133kmph; but up to 90 % in other positions. As described in DDEN 5 (v-05), TCE did not consider increase by 33 1/3% for the wind load but considered permissible "Equivalent stress of 0.9 fy" as per para 7.1.4 of IS 800-1984. TIFR also sought advice from Mr Lee King, a senior antenna specialist from the National Radio Astronomy Observatory as discussed in Section 5. In Section 6 is discussed automatic stowlocking of the antennas. Proposed review of some aspects of the structural and mechanical design of the 45 m antennas of the GMRT by TCE is discussed in Section 7. Discussions and Conclusions are given in Section 8.

It is planned to include original or Xeroxed of the documents listed in References in Part B of this Report as part of GMRT antenna archives at NCRA. Part C would include Xeroxed and soft copies of the Design Notes by TCE including those detailed in the nine Computer files giving structural analysis of the GMRT dishes and concrete tower.

3 Maximum value of the dead loads and wind loads near the focus of the dishes on the top of the quadripod.

In the introduction to the Report titled TCE. G18/DR/CAL/153-DISHCRAD dated 18 Feb. 1990 , it is stated in "Section 2.1.3, "Other Loads: A load of 1300 kg is assumed as the weight of the feed drive system, rotating feed cage, feeds and attachment of feeds to the feed cage. A moment of 12000 kgcm is assumed for the unbalanced dead load about the axis of the system". Details of the loads of the antenna feeds and electronics being placed near the focus were not given as these were still in development. NCRA/TIFR had specified in 1988: ‘(a) load at the focus of 250 kg excluding structural steel and motors and (b) wind force on an area of about 2 sq. m. due to dipoles and RF boxes’ (Report by TCE titled ‘GMRT Mechanical System’, vide their letter G18/664 dated 27/7/1990). In 1988, Parikh of TCE had made an analysis of some of the feeds being developed (copy of this report is available as archive at NCRA) but it needs complete revision. Subsequently, as I recall on my request in 1992, TCE calculated various dead and wind loads including those of the thin bearing, rotating cage, drive system, stools, front-end electronics boxes and various feeds. That report, if it was done, needs to be located. Nevertheless, I understand that TCE has now been requested to take a fresh look at allowable loads, including proposed modifications of the antenna feeds and drive system. *I may suggest that any new feeds, including test feeds, should be placed on the rotating turret in future only after clearance by a technical note regarding the admissible dead loads and wind loads, and if required after referring to TCE, particularly if the surface area is large and also weights of the feeds.*

Suitable counterweight should be placed on opposite faces of the rotating feed cage turret, in order to ensure that there is no extra load on the feed drive system. This was done during 1991-94. Finally, implication of any extra loads near the focus should also be evaluated considering balancing of the entire dish along the elevation axis. During the construction and erection of the dishes in 1990s, suitable counterweights were placed by the antenna contactors for overbalancing the dishes by a small value so that they would get rotated towards the zenith, in case of a failure of the brakes on the elevation motors, a practice that is carried out for several antennas constructed internationally. BC Joshi and the present author developed a procedure for the purpose of balancing along the elevation axis, as is described in an Internal Technical Report of NCRA. I may add that overbalancing is desirable, if practical, but perhaps not essential.

In 1988 I firstly did not plan a DC drive with DC brakes for rotating the turret near the focus as DC brakes had given problems at Ooty (we realized later that the current to the DC brakes should not be applied suddenly as it leads to their wear out). Hence, I suggested using a worm gearbox since it is not reversible between the turret and the motor. Unfortunately worm gearboxes have appreciable backlash. (Backlash of the gear boxes supplied by New Allenbury was found to be large and was minimized by reducing distances between the gears of the worm at the NCRA workshop; it is possible that the backlash may have increased now due to wear and tear). Later we imported DC motors had a DC brake. It was a mistake of not using a normal involute gearbox with low backlash. I understand from B. C. Joshi that a new feed drive system with absolute encoder is planned. I suggest that the worm gearbox may also be replaced by an imported compact involute gear box with low backlash. It should be planned with priority, in order to optimize positioning of the feed turret box.

4 Survival Wind Specification and its implications

Since wind loads on outdoor structures are proportional to the square of wind velocity (= 0.5 ρ v^2), specification of the maximum wind velocity likely to occur in the expected life time of the structure, say 50 years, is very important for selection of the structural members of the antenna by the design engineer, in order to ensure its safety.

Based on the maximum 3-second-peak wind velocity recorded at Pune by *the India Metrological Department (Simla Office)* for each of the 35 years from 1948 to 1982 years, a 50 year and 100 year "basic wind velocity" (so called survival velocity) was determined by Kapahi and Swarup (1986) For this analysis a procedure discussed in Narasimha and Shrinivasan (1983) was followed, which was similar to that given in Section 2.2.4 of Sachs (1978). A value of 127 kmph for a 50 year return period and 136 kmph for a 100 year return period at 10 m height was determined. Fig. 2 of Kapahi and Swarup is included here as Fig.1. M C Sharma (1985), a very senior scientist of the Simla office of IMD kindly provided results of his analysis which gave basic wind speed at 10 m height for the return periods of 100 and 150 years to be 128 kmph and 132 kmph respectively for Pune. The maximum wind encountered at Pune in 35 years from 1948 to 1982 was 125 kmph at 10 m height. However, around the same time a draft revision of the ISI code IS:875 (1987) recommended a value of 140 km/hr (39m/s). Usually radio telescopes are stowlocked in zenith positions whence stresses in the structural elements of the antennas and torques applicable to the gear boxes are appreciably lower. Automatic stowlocking was also considered for the GMRT antennas. Hence, TIFR suggested to TCE to use a 33 year return survival wind of 133kmph (37.0 m/s) by using a risk probability factor of 0.95 along with the IS:875 (1987) basic wind velocity of 140 kmph (see Detailed Design Engineering Note, DDEN 4, by TCE dated 1989-12-06).

As discussed in Section 5, it was *suggested to consider maximum allowable stress value of only 65% of the yield strength of the structural members for the bending moment case in the stowlocked zenith position of the 45m dishes to ensure their safety, when subjected to the specified "survival wind velocity" of 133kmph; but up to 90 % of the yield strength in other positions***.** *In April 1989***,** I sought comments and advice regarding various design parameters of the 45m dishes from Mr Lee King, a very senior antenna specialist at the National Radio Astronomy Observatory, USA (my letter to him: Swarup 1989 and his reply, Lee King 1989 are available in a file as part of archives at NCRA). I quote from Lee King's letter: "***For a solid surface antenna, the wind induced forces on the structure at any elevation may be 20 to 100 % higher than at zenith. The probability of both 140 km/hr wind and unable to stow the antenna is very slim. I would use a higher risk factor for this case in design". He further stated: "Allowable stresses are given by AISC specs. section 1.5. Increase of 1/3 is allowed for wind induced forces, detail see AISC spec. section 1.5.6."***

In 1993, I obtained maximum value of wind velocity recorded in Pune up to 1990 and wrote a "Note to all concerned persons" with copies to all senior persons at NCRA/GMRT giving the maximum values of the wind in each year from 1948 to 1990 (Annexure A1). It was noted that 'winds reached highest value mostly during the months of April, May or June. *We must take all steps for automatic stowlocking if mean wind over a period of half a minute exceeds 45 kmph'*. Since the cup anemometers at each antenna are installed at a height of ~ 20 m, these record a value of wind velocity that is higher by about 1.07 times compared that at 10 m height (see IS 875). This is one of the reasons for my present recommendation that antennas are to be stowlocked only when wind velocity averaged over one minute exceeds 50 kmph.

In June 1998, I requested Gp. Cpt. Krishnamurthy, the Senior Administrative Officer at NCRA, to obtain data of the maximum wind velocity recorded at the Lohagaon Airport near Pune. He was given by them data of the "Strongest Surface Wind 1960-1997." *I was rather* *surprised to note that a wind velocity of 148 kmph was noted at Lohagaon Airport on June 14 1992!* This was alarming as wind forces are proportional to the square of velocity. I wanted further information such as height and type of wind instrument used etc. Hence, I wrote a note on 31st March 1999 to Gr. Cptn. Krishnamurthy for a follow up and later to Prof. Ananthkrishnan on 9th August 1999 but perhaps it was not followed up. It is important to contact both IMD at Simla office and the concerned person at the Airport to get all available data and details of the wind meter at Lohagaon airport. I would be very interested to join the NCRA scientist or engineer for the above follow up as I have made a study about the various types of the wind meters.

Recently, a detailed paper has been written by N. Lakshmanan et al. (2009) of the Structural Engineering Centre (SERC) of CSIR in 'Current Science' tiled "Basic wind speed map of India with long-term hourly wind data". In Annexure A2, we reproduce Table 1 of their paper recommending "revised basic wind" velocities for many stations in India including Pune. For the Lohagaon airport, they derive a value of the return period T = 50 years of 43 m/s = 155 kmph. However, Lohagaon airport has terrain category 1 (open terrain..) but for the GMRT antennas, terrain category 2 seems more suitable (see IS;875, page 8). Using values of k_2 from Table 2 of IS:875 (1987) for the two terrain categories, we determine the value of basic wind velocity for the GMRT site as (1.07/1.12) x 43 m/s = 41 m/s = 148 kmph. As was pointed out earlier, the GMRT antennas are designed for 133 kmph and hence a wind of even 148 kmph could be harmful not only for the structural parts but also for the mechanical drive system, unless antennas are stowlocked.

I have written to SERC requesting them to give us a copy of the data and graphs plotted for Pune and Lohagaon, on which basis they have arrived revised values for Pune (category 3) and Lohagaon airport (category 1). I have also requested their advice regarding the expected value of wind speed for the 50 year return period at the GMRT site (category 2), located~ 60 km north of Pune. However, we may have to take our own decision. This is why I am suggesting to TCE to calculate stresses for 37 m/s, 39 m/s and 41m/s, particularly for those members with high values of stress.

It was proposed to install an accurate wind meter, with UPS battery back up at the central square of the GMRT 15 years ago that would have recorded maximum winds each year in spite of any power failure during a storm. I understand that recently a wind meter supplied by ISRO has been put in the housing colony which is category 3 site. NVN told me recently that the wind meter is perhaps located at a height of <10 m. In my view a reliable wind meter should be installed at a height of 10 m at the central square, away from buildings, tall trees and other structures, so that we can correlate statistically wind velocity values at the GMRT site with those at the Lohagaon airport, and make our own estimates of the "basic wind velocity".

Also it would be very useful to obtain every day maximum value of the wind velocity recorded each day by the two wind meters installed on each of the 30 antennas. It is possible that higher winds may be occurring near some of the antennas on an average, particularly during a gust exceeding 50 kmph or 80 kmph, e.g. at W5 which is on a ridge and perhaps also at S4 that is nearly 200 m away towards west of a ridge. Since the wind velocity values measured by the cup anemometers of all the 30 antennas is sent by telemetry to the Control Room computer, a relatively simple analysis programme should be developed, with priority, that summarizes statistics of the wind velocity measured at the 30 antennas, viz. (a) peak values of the wind velocity occurred in a day for the ~3-second data of the two cup anemometers and time of occurrence and (b) peak of the average values over 1 minute and time of occurrence (9 columns). In case the wind velocity exceeds 90 kmph (occurring only once every few years), the wind velocity for the ~3-second data may be stored for +/- 3 hours of the occurrence of peak wind velocity. Such a data would be very useful to understand as to how rapidly the wind velocity changes from a value of 50 kmph to more than 100 kmph and also extent of the area with very high wind velocity in the GMRT region.

It is important to note that a 50 year return period does not imply that the structure (GMRT antennas) will be safe for 50 years! I quote from Section 2.4.4 (iii) of Sachs (1978): Calculated Risk: "The maximum velocity V_{max} for a return period of T years is obviously itself a statistical average, based on the average value of several T-year periods. It has been calculated (Whittingham 1964) that V_{max} has a 63% probability of being reached in T years, so that a structure, if designed to Velocity V_{max} has a 63% chance of failure". I give further details in Annexure A3.

In 1986, M. C. Sarma, senior metrology scientist at the Simla office, wrote to me that the cup anemometers do not give peak value of the gust during a severe wind storm and only instruments such as Pressure Dynameters provide that (also see Sachs 1987). However, the cup anemometer is likely to give 1 minute average value correctly even during a storm.

To summarize this section, it is very important to review possible implications of the occurrence of wind velocity exceeding 133 kmph at 10 m height at the location of the antennas of the GMRT. It is extremely important to ensure that antennas are stowlocked when wind velocity exceeds 50 kmph as discussed further in Section 6. In case of occurrence of winds of > 100 kmph at any of the GMRT sites, it would be useful to record the damage seen around the surrounding regions, such as number of falling of trees and of LT and HT lines, etc. That data would be useful to understand the area covered by the storm. Since such high winds occur only every few years it would not be taxing but educative to the GMRT maintenance engineers, scientists and astronomers.

5 Wind Drag Factors for the Wire Meshes of Low Solidity

The reflecting surface of the 45m dishes consists of stainless steel wire mesh made of 0.55mm wires with mesh sizes = 10 mm x 10 mm, 15 mm x 15 mm and 20 mm x 20 mm for the inner, middle and outer parts respectively. In 1987, TIFR requested the National Aeronautical Laboratory (NAL), Bangalore, to carry out 'wind tunnel testing of screen elements used for the GMRT' (NAL FM 8723, October 1987). Wire meshes of size 6 mm X 6 mm, 12 mm x 12 mm, 15 mm x 15 mm, 20 mm x 20 mm and 24 mm x 24 mm all made of 0.55 mm diameter were supplied by TIFR. The wire meshes were mounted by NAL on a ring of "a thickness of 10 mm and 755 mm outer diameter." The ring was mounted on a strain gauge balance that was calibrated in the presence of Mr. Tapde, Mr Karthikeyan and me. The measured values of Cd by the NAL in the normal direction ranged from 1.05 to 0.82 for 5 different sizes of meshes (6mm, 12mm. 15mm, 20mm and 24 mm), being ~ 1.05 for the 6 mm x 6 mm mesh and ~ 0.82 for the 24 mm x 24 mm mesh. These values seemed appreciably lower than the expected value of ~ 1.2 for a round wire.

Not many measurements were available in 1988 for Cd of sparse wire mesh. TCE preferred not to use values of Cd measured by NAL as these seemed rather low. The available value in the literature was by (a) Cohen (1964) as Cd = 1.3 at $\theta = 0^0$ (normal to the surface) but size of wire meshes was not given and (b) Wyatt (1964) for a 7.87 x 7.87 x 1.1 wire mesh giving Cd = 1.55 at 0^0 varying to 0.2 at 90^0. TIFR had also obtained privately values measured by Koppen of Netherlands that gave Cd = 1.46 at 0^0 and ~ 0.4 at 90^0 for a mesh of size 15 mm x 15 mm x 1.4 mm. Based on the above data, TCE decided to use a conservative value for the Cd of 1.42 at $\theta = 0^0$, ~ 0.8 at 50^0 to the normal,~ 0.53 at 80^0 to the normal and 0.4 at 90^0 (see curve 5 of Fig. 2).

In 2007 I made a Google search and came across a paper by Richard and Robinson (1999) who plotted the measured values of Cd of wire meshes of different solidity based on their own measurements and values from the literature. **They concluded that the value of Cd decreases with decreasing value of solidity. They derived an equation giving Cd values a function of the solidity**. I have re-looked at the NAL report (1987) and noted some errors in the derived values as a result of wrong value of the area of the meshes measured. I have made corrections to the same. My values nearly agreed with the corrected values determined by M.K.S.Yogi in 1989 (DDEN-1). Using the relation between Cd and solidity of the wire mesh given by Richard and Robinson (1999), I have calculated Cd values for various sizes of mesh of low solidity and find reasonable agreement between NAL measurements and calculated values (Swarup 2007; Annexure A4 reproduces Table 1 of Swarup 2007 with some recent data added). The calculated values are also in agreement with the measurements made in Japan by Murota (1976). Further, the well known Structural Engineering Research Centre at Chennai (SERC) has recently measured Cd of a welded wire mesh of size 6 mm x 6 mm x 0.55 mm, as requested by NCRA; SERC has derived its Cd value close to 1.0 (Fig. 3), much lower than other values in the literature!! NAL value for that mesh is 1.33 and is nearly the same as the calculated value using the equation derived by Richard and Robinson. Further, the measurements made and data from the literature by Richard and Robinson and measurements by SERC indicate that Cd decreases as $\cos^2 \theta$, with $\theta = 0^0$ in the normal direction and 90^0 in the plane of the mesh.

I may note that measurement of Cd of thin spare wire mesh is not easy requiring sensitive strain gauge balance. What is most important is the Cd value for wind velocity normal to the surface. During 1950s measurements of pressure drop across the sparse wire meshes were made by blocking the wind tunnel by one or a few parallel wire mesh and measuring pressure on both sides and thus the pressure drop. Wind tunnels of smaller diameter are now available at a number of institutions in India, NAL, IISc, and several IITs. In view of the continuing use of sparse wire mesh for the parabolic dishes operating at dcm and metre waves, for which India is a leader, I suggest that NCRA should get such measurements made and publish a paper discussing all aspects. Nevertheless I am convinced that a lower value of Cd should be used for the GMRT dishes in the new analysis being done by TCE.

To summarize, I recommend a value of Cd of 1.2 at $\theta = 0^0$ for the 10 mm x 10 mm x 0.55 mm mesh, 1.1 for the 15 mm x 15 mm x 0.55 mm mesh and 1.0 for the 20 mm x 20 mm x 0.55 mm mesh in the inner, middle and outer 1/3rd portions of the GMRT respectively, decreasing as $\cos^2\theta$ up to ~ 0.2 at 73^0 and remaining 0.2 up to 90^0 (Curves marked as D, E, and F in Fig. 2 of this Report).

6 Structural Analysis of the 45 m Dishes made by TCE in 1989 and maximum Allowable Stress in the Structural Members

6.1 **Brief history:** The SMART concept consisting of rope trusses attached to parabolic frames supporting sparse wiremesh of low solidity for the reflecting surface was proposed in May 1986 (Swarup 1986). This concept and other possible alternatives were discussed in detail in a 2-week design review meeting held at Bangalore in late July/ early August 1986, which was attended by Dr. Ben Houghoudt, an expert antenna engineer from Netherlands and the designer of the WSRT 25m antennas, whose visit was arranged under an Indo-Dutch Scientific Exchange programme. Dr Houghoudt supported the SMART concept. He suggested the 45 m antenna to consist of 16 parabolic frames connected to a hub supported by 4 stiff points, 2 to a bull gear and 2 elevation bearing support. Later in 1986 and early 1987, TCE also examined a conventional design and also a preloaded parabolic dish. A concept report was prepared based on over several technical notes and computer analysis (TCE 1987: NCRA archives). In 1988 a prototype 45 m parabolic dish was fabricated at Ooty that showed satisfactory performance with no noticeable vibrations of the structural members and rope trusses. Finally the SMART concept was adopted (see GMRT revised Project Report Oct 1988).

During 1988 and 1989, M/s Tata Consulting Engineers (TCE) made exhaustive computer analysis of the structural designs of the 45 m dishes. The designs were based on eleven “Detailed Engineering Design Notes (DDE Notes)” (see Part C). Several design reports were discussed in detail with the GMRT scientists and engineers. The design reports considered engineering codes and practices in India. TCE developed special computer programmes for the analysis, an excellent job. Computer analysis was documented periodically. Basic design was finalized by April 1988 and tenders invited. Seventeen bids were received. Two contractors were selected for the fabrication and erection of 15 antennas each, namely M/s Jog Engineering Ltd., Pune and M/s Southern Structural Ltd., Chennai. Designs were finalized and drawings for the fabrication and erection of the mechanical and structural parts of the 45m antennas were released by November 1989.

6.2 **Design notes, analysis and computer outputs**: We list here 9 computer files produced by TCE that describe design basis and computer outputs concerning (a) parabolic dish including the quadripod and the hub, 2 files, (b) cradle supporting the dish at 4 stiff points, two supports at the opposite ends of the bull gear for the elevation drive and two at the elevation bearings and (c) the Yoke connecting the cradle and the dish to the slew ring bearing for the azimuth drive, 2 files (d) rms bias errors, (e) rms error, (f) RCC tower of the 45 m antennas and (g) dish erection. In each of the files as listed below, such as (TCE.G18/DR/CAL/153----), firstly a detailed technical note is included, describing design criterion, computer models and computer programmes used, analysis made, results, references and a table that gives list of computer output tables. These technical notes as introduction to the computer files are being copied, as coordinated by me, and will be archived at the NCRA library and will also be scanned (as Part C).

C0: Eleven "Detailed Engineering Design Notes (DDE Notes)" by TCE giving design basis for the 45 m dishes of the GMRT.
C1: TCE.G18/DR/CAL/153-DISHCRAD, dated 18/20 Feb 1990 (final **space truss** pin-joint analysis of the 45 m dish, giving input data, displacements and stress ratios).
C2: TCE.G18/DR/CAL/153-CRADLE, dated 19 Feb 1990 (final analysis of the cradle).
C3: TCE.G18/DR/CAL/153-RIGIDISH" dated April 23 and 28 1990 (the structure of 45 m dishes is considered as a rigid space frame).
C4: TCE.G18/DR/CAL/153-YOKE-01-R1 dated 07-03-90, gives stresses, displacements and forces and moments at the elevation and azimuth bearings)
C5: TCE.G18/DR/CAL/153-YOKE-STIFFNESS-01-R1 dated 18-07-91; (as above and also natural frequencies).
C6: TCE.G18/DR/CAL/153-RMSBIAS dated 22-06-90; (rms errors if initial coordinates of the paraboloid are biased to various zenith angles of the 45 m dish).
C7: TCE.G18/DR/CAL/153-RMSERR dated 22-06-90; (displacements of best fit parabola and rms errors).
C8: TCE.G18/DR/CAL/153-DISHERECTION dated 10-04-91.
C9: TCE.G18/DR/CAL/153-RECT dated 05-07-1990, "Analysis and design of the reinforced concrete tower".

As noted earlier, design considerations for the structural design of the GMRT 45 m antennas have been described in the papers by Janardan, Yogi and Swarup (1990) and Janardan, Yogi, Swarup and Tapde (1991). We discuss below design input assumptions and specifications, the main aim of this Technical Report.

6.3 **Design input specifications**: There are four major design considerations for the structural analysis: (a) Wind speed and loads (b) Shielding and force reduction factors , considering shielding of the back side members of the trusses by the front members' (c) Stress increase factors due to joint rigidity and (d) allowable maximum stress.

6.3.1 *Wind speed and loads*: see Sections 3 and 4.

6.3.2 *Shielding and force reduction factors:* All of the structural members of the parabolic frame and other trusses of the 45m dishes consist of round tubes. For analyzing the wind forces on the structural members of the dish, TCE considered wind forces on the total projected area of all members of the triangular trusses but applied 'overall force reduction factors = 0.78 in order to account for the shielding effects by the front members of the trusses of the antenna structure for the horizon orientation and 0.68 for the zenith case considering also adjacent frames of the antenna (ISI documents do not provide any guidelines for parabolic dish antennas). These factors may be reviewed.

6.3.3 *Joint rigidity and* ***stress increase factors***: The structural design of the 45 m parabolic dish and cradle was done by TCE (M.K.S. Yogi and colleagues), assuming pin-jointed space frame. As described in the Technical Notes as Introduction to the Computer output, TCE.G18/DR/CAL/153-DISHCRAD, dated 18 Feb 1990: "The structure was considered as a space truss with 3-degrees of freedom per joint along the X, Y and Z direction". However, since the structural members of the GMRT antennas are all welded, TCE considered stress increase factors for joint rigidity of ~ 1.2 and 1.25 for the main chord members of the triangular trusses of the 45 m dishes and 1.40 to 1.65 for various bracing and strut members (see Table 5 of the Technical Note as Introduction to DISHCRAD; also DDEN 11, v-11), in addition to stresses determined by the pin-joint analysis of the dish structures. *The stress ratios given above were the basis for the final design of the GMRT antennas.*

6.3.4 *Maximum allowable Stress*: As discussed earlier, TCE was advised to consider maximum allowable stress value of 65% of the yield strength, fy, of the structural members in the stowlocked zenith position of the 45m dishes in order to ensure their safety when subjected to the specified "survival wind velocity" of 133kmph; but up to 90 % in other positions. Permissible stresses used by TCE in 1988-1989 are described in DDEN 5 (v-05), where it is noted on page 3 that TCE did not consider increase by 33 1/3% for the wind load but considered permissible equivalent stress of 0.9 fy as per para 7.1.4 of IS 800-1984. For the new analysis one may consider recommendations of IS800 2008-draft.

6.4 **Computer Outputs**: During 1988 and 1989 TCE gave TIFR periodic progress reports, minutes of discussions, computer outputs and design drawings of the GMRT antennas. There are 8 major computer outputs regarding analysis of the GMRT antennas and another for the RCC tower. As noted earlier, design of the GMRT antennas was done on the basis of Detailed Design Notes 1 to 11, and the computer analysis given in DISHCRAD (including a technical note as an Introduction therein). I describe DISHCRAD report in more detail than others, as it gives analysis (displacements of the joints, stresses of members etc.) of the structural parts of the quadripod, parabolic frames, rim and the hub for the selected design that was used for the final fabrication of the 45m dishes.

6.4.1 ***DISHCRAD***: The Computer file named as TCE.G18/DR/CAL/153-DISHCRAD dated 18/20 Feb 1990 includes firstly a technical note (see its copy in Part C of this Report) that summarizes design considerations (22 pages from pages 23 to 44 of the DISHCRAD computer file). "The structure was considered as a **space truss** with 3-degrees of freedom per joint along the X, Y and Z direction". The above file gives 8 computer outputs giving input data and results of the analysis of the GMRT 45m dish (pages 45-188). The 'file' (in hard cover) also has TCE.G18/DR/CAL/153-CRADLE dated 19 Feb 1990 giving technical notes, summary of results and computer output for the analysis of the cradle.

6.4.1.1 *GMRT 45m parabolic dish*: As shown in Figures 4, 5 and 6, the 45m diameter GMRT dish consists of 4 legs of a quadripod supporting antenna feeds at the focus, 16 parabolic frames, connected by 16 rim trusses near the rim of the dish and the central hub. The focal length is 18.54 m. The elevation axis is perpendicular and displaced by 600 mm away from the Azimuth axis. All the above members consist of triangular trusses with 3 members at each joint. The hub is supported at 4 relatively 'rigid' points to a cradle, two connected to the Bull gear for elevation drive and two connected to shafts connected to elevation bearings placed on the Yoke that is placed on slewing bearing for azimuth rotation.

6.4.1.2 The computer outputs of DISHCRAD give the input data, deflections (displacement) at all joints and stresses in all the tubular members, tie rods, rope trusses, etc. As summarized on page 123 of the DISHCRAD output, there are 6999 members in each dish, with 1982 joints, the number of displacements at each joint being 3. There are 787 wiremesh panels.

Basic wind velocity at 10 m height = 140 kmph (39 m/s) but probability factor k1 = 0.95 (thus maximum wind velocity, V_b = 140 x 0.95 = 133 kmph = 37m/s), topography factor k3 = 1 (since large around the GMRT antennas is fairly level ground with not many buildings and trees), structure size factor k4 = 1 and 'terrain category, 2'; k2 (z) gives wind speed factor for height z as per IS:875 for class A structure. Details regarding the factors k1, k2 and k3 are given in DDEN 4 and should be used rather than those in this summary. Wind velocity for design V = V_b . k1 . k2(z) . k3 . k4 and pressure, q_z = K . Vdz^2, where air density K = 0.057 based on air density of 1.106 Kg/cu.m at an elevation of 650 m above mean sea level for the GMRT antennas. At 30 m height, k2 = 1.12 and hence, V = 39 . 0.95 . 1.12 . 1 . 1 = 41.44 m/s, giving wind pressure q_z = 0.057 . $(41.44)^2$ = 98 kg/m^2, (for approx. checks: TCE has considered pressure for different heights of the GMRT antennas as relevant).

Dead load facing sky = 92 ton as per TCE, (dish + cradle being 47 ton: I assume 34 ton for the dish and 13 ton for the cradle and bull gear) and 45 ton for concentrated load (counterweight =29 ton + ?: I thought that the counterweight was ~ 29 ton: to check). Inspite of seeing several computer output files, I am a bit unclear as to the actual weights of various part of the dish. I plan to search a copy of the final bill of materials by TCE and the bill of M/ s. V.M. Jog that correctly gives weights of various parts. Mass moment of inertia along x, y (along elevation axis) and z axis (vertical axis) = 7.3, 7.4 and 8.4 x 10^7 kg-cm-sec.

6.4.1.3 ***Results in brief***:

(5.4.1.3a) ***Wind loads*** *on El Axis (pages 123-125 of the DISHCRAD-02 computer output):*

Dish at Zenith (90^0): Side wind: Structural members 27.6 ton, Wiremesh 7.1 ton; Total = 34.7 ton
Dish at 15^0 elev.: Front wind: Structural members 31.1 ton, Wiremesh 15.6 ton; Total = 46.7 ton

(Comment by G Swarup on 230509): It is noteworthy and plausible that the calculated value of wind loads for the wiremesh for the dish at zenith (side wind) is nearly half (7.1 / 15.6 = 0.46) of that for the dish at a 15^0 elevation (front wind). But the wind loads for the structural members are about 90% (27.6 / 31.1 = 0.89) for the wind loads for dish at zenith than the value of 27.6 ton for the dish at elevation of 75^0. Considering the wind tunnel measurements for the scaled model of the GMRT 45m dish carried out by the University of Roorkee in 1988 that gave the force coefficient of 0.78 for an elevation of 10^0 and 0.55 for elevation of 90^0, I would have expected a value for the structural members for the side wind case of (0.55/ 0.78 x 31.1 ton) = 21.9 ton. But on the other hand the difference may be due to the quadripod that was perhaps not connected in the scale model tested by the University of Roorkee. A value of 27.6 ton for the zenith case could be partly due to higher wind loads on the quadripod legs and perhaps also perhaps due to a conservative assumption by TCE for the shielding of back side members of the structural frames (see Section 5.2 (b)). It would be useful to get a Computer Fluid Dynamics (CFD) analysis done for estimating the wind loads on the structural members of the dish at zenith and at elevation of 75^0. I understand that for the 32m dish constructed in 2008 near Bengaluru, ISRO did not use the values of forces and moments given by Cohen et al. (1964) based on wind tunnel measurements but used CFD analysis.

It is interesting to make a rough check for the wind load on the wiremesh = 15.6 ton, derived by TCE for the front wind at 15^0 elevation angle. The total area of the 45m dish is 1590 m^2. Solidity of the wiremesh is 0.028, 0.080 and 0.103 for the 20 mm, 15mm and 10 mm mesh respectively that cover 1/3rd area each of the dish (ref. A4). Thus average solidity = 0.211/3 = 0.07033. Wind drag factor assumed by TCE = 1.42. Wind pressure = 98 kg/m^2 (see Section 5.4.2; basic wind velocity). Therefore, wind load on the mesh for dish to the horizon = 1590 x 0.07033 x 1.42 x 98 / 1000 = 15.56 ton that compares closely with
value of 15.6 ton derived by TCE. Hence if the average value of Cd is taken as 1.1, we would have the wind load on the mesh of only ~ 12 ton. The total wind load including that on the structural members would be 31.1 ton + 12 = 43 ton rather than 46 ton. I may add that the dish has dead load of about 40 ton. Wind load is in the horizontal direction and dead load in the vertical direction. Only an appropriate computer analysis could derive actual stress on the structural members due to a lower value of the Cd for the wiremesh. Nevertheless, I may add that I see no justification for using the value of 1.42 for the review being done,

(5.4.1.3b): Specifications of R.M.S. error: According to TCE-DDEN V-06, page 4, the R.M.S. surface error were specified in 1989 as follows: (a) *12 mm, 6 mm and 4 mm due to the errors of the plane wire mesh facets* for the outer, middle and inner 1/3rd area; and (b) *total rms error were specified as 24 mm, 12 mm and 8mm including (c)displacements by dead load, and wind load of ~ 20 kmph, and fabrication errors. From the above values I derive* ***rms errors due to (c) as follows: $(24^2 - 12^2)^{0.5}$ = 20.8 mm, 10.4 mm and 6.9 mm for the outer, middle and inner 1/3rd area respectively with peak errors being twice of the above values(with peak to peak errors twice of the above!)***. As described in Annexure A6, obtained from the computer outputs of RMSERR , the overall rms error of the parabolic frames for DL and WL at 20 kmph is < ~ 4 mm. (Section 5.4.1.3d). Hence any larger errors, according to the above specifications would be due to fabrication errors. But as I recall, that in our contract we specified lower values of the overall peak errors of (12, 8 and 4?) mm for outer, middle and inner areas. I plan to check from the contract specification book i.e. the so called black book). Nevertheless, the fabrication errors according to a theodolite survey of several thousand points for 20 antennas in 1996 or 1997 are considerably larger than was given in the contract specification book, particularly for certain antennas (derailed information is available with Shri G. Sankar and also in the arbitration papers of Jog Engineering). These could be corrected if large errors are for the Stud supports at PRFs that support rope Trusses but not straight forward if large errors at the intermediate supporting points of the rope trusses. All can be minimized in principle but time consuming. Perhaps one may consider correcting the surface along-with the painting job, if practical, particularly for antennas with large errors. Also one may consider using 6mm x 6mm x 0.55mm mesh for the

inner 1/3rd area as its replacement could be done perhaps within a month, with about 12 or 15 workers for each of the 30 antennas, 6 workers working on two opposite sides. This would cut down contribution by the ground temperature due to the leakage of the wiremesh at 21cm.

(5.4.1.3c): R.M.S. bias as per computer analysis: In 1989 and 1990*,* TCE made a systematic calculation of the rms errors of the 45 m diameter paraboloid of the GMRT antennas. In several microwave antennas, the surface values of the paraboloid is specified at a zenith angle of 30^0 or 40^0 by considering (i) the theoretical geometric values of the paraboloid and (ii) the calculated distortions by gravity at that zenith angle, in order to minimize rms errors from the zenith to horizon. This is called biasing the antenna. TCE made calculations of the bias for different zenith angles (TCE.G18/DR/CAL/153-RMSBIAS dated 22June 1960). Since the gravity distortions were relatively small for the GMRT dishes, we did not use biasing values, as I recall.

(5.4.1.3d): RMS errors as per computer analysis: The computer analysis output file (TCE.G18/DR/CAL/153-RMSERR dated 22-06-90) gives detailed values of the displacements (Δx, Δy, Δz) of the GMRT 45m dishes at different zenith angles and also gives rms values of the errors of the surface. It may be seen that the rms error of the dish is < ~ 4mm at various zenith angles (Annexure A6). Displaced coordinates of the focal point of the best fit paraboloid of the 45m antenna are also listed in the above Computer output file and are < ~ 5mm.

*(5.4.1.3e****): Displacements of the top of the quadripod*****:** Displacement of the top frame of the quadripod, when the dish is rotated at an angle of 75^0 from the zenith (elevation $\theta = 15^0$), is calculated by TCE as 8.1 cm towards the ground (page 129 of the DISHCRAD file). The displacement of the joints of the parabolic frames is relatively small as described in Section *(5.4.1.3d).* Therefore, the pointing error of the dish will change in elevation by $\Delta\theta$ = -(8cm/2180) radian = -12.6 arcmin. The pointing error is likely to change by $\Delta\theta$ = -12.6 x cos θ at other elevation angle. This expectation needs to be checked by astronomical measurements and also by photographic measurement with a camera with a 10^0 field of view or narrower. Also, the top of the quadripod legs gets displaced towards the ground by the dead load near the focus for the zenith case by ~ 3 cm that would lead to defocus of the dish by a relatively small value that will change with zenith angle, perhaps as a cosine of the angle. As a compromise the 21cm feed may be displaced upwards by ~ 1.5 cm towards the zenith for obtaining best performance. However, the present L band feed is rather heavy and not easy to move in z with small displacements to check the efficiency.

6.4.2 ***RIGIDISH*****:** Although the design and fabrications of the GMRT dishes was based on DISHCRAD analysis, TCE also made an analysis for the “rigid dish” in April 1990 resulting in the computer file “TCE.G18/DR/CAL/153-RIGIDISH” dated 23/28 April 90. In the technical note as introduction to the RIGIDISH computer output (Part C of this Report), it is stated that “The structure is considered as rigid space frame with three translational degrees of freedom per joint along the X, Y and Z directions and three rotational degrees of freedom per joint about X, Y and Z directions”. ***I have recently made a comparison of stresses determined in some of the typical members of the GMRT 45 m dishes according to the computer outputs of the DISHCRAD and RIGIDISH***. A brief comparison is given *in Annexure A5* for some typical cases with relatively high stress factors. For both DISHCRAD and RIGIDISH, TCE has computed **stress factors** for all the members of the quadripod, and the 45m dish (rim ,prfs and the hub) for a wind at 10 m height of 133 kmph including its variation with height. I assume that the stress factor is the fraction of the yield strength, fy, (to check from Shri Yogi). **From a limited study of the computer outputs of DISHCRAD and RIGIDISH, I find that the stress factors are generally lower in the latter case by about 5% to 15% for the main members of the quadripod legs, prfs and rims but are lower by about 30% for the bracings and struts. It is noteworthy that the stress factor for the RIGIDISH are smaller than 0.66 for all the members of the 45m dish, except for some parts of PRF-3 having stress factor = 0.72.** However, the stress for the top frame of the quadripod for the case of DL seems to be about 20% higher for the RIGIDISH than for the DISHCRAD case (?), and thus the resulting stress factor is close to 1. Also the stress factors for several members of the hub is about 10% higher for the RIGIDISH being ~ 0.89.

6.4.3 *Rigidity considerations:* If the RIGIDISH analysis (clamped-clamped constraint?) is considered preferable by TCE in the new analysis being done than the pin-joint analysis including consideration of the stress increase factors in 1989, it would imply that the stress increase factors considered for the pin-joint analysis and assumed stress increase factors by TCE based on a limited analysis were somewhat conservative. This may imply that the 45m dishes could be safe for somewhat higher winds. However the stresses are close to 1 (presumably up to fy) for some of the main members of the hub for the wind velocity of 133 kmph for both the DISHCRAD and RIGIDISH analysis. The safety consideration of the hub members in case of very high winds may need more study.

The major question is as to what are applicable constraints to be considered for displacements and rotations of tubular members of trusses in which all joints are welded, in order to take care of rigidity, according to the IS and international codes and practices

I may add that the welding of the GMRT dishes was closely monitored by two experienced engineers of TCE from their construction division and the GMRT staff, all coordinated by the Project Manager, Shri S.C. Tapde. About 10,000 X-ray images were taken.

6.4.4 *Yoke*: The computer output TCE.G18/DR/CAL/153-YOKE-01-R1 dated 07-03-90, gives design parameters, stresses, displacements and forces and moments at the elevation and azimuth bearings. Some of these results are summarized in Part C. Further, TCE.G18/DR/CAL/153-YOKE-STIFFNESS-01-R1 dated 18-07-91gives the above data and also natural frequencies of the Yoke. Based on these data, the locked rotor frequency of the GMRT 45m dish including the stiffness of the planetary gear box was calculated by the TCE project coordinator, Gajria (1990). Also, Swarup and Girish Kulkarni (1991) calculated both the controlled and uncontrolled frequencies that will be described in another internal technical report.

6.5 Reports of the Structural Analysis of the 45m dishes:

Recently I have searched and scrutinized ~ 100 files including ~ 20 computer output files of TCE. These files are stored in a few cabinets and almirahs at NCRA and some at GMRT. Many of these files were given to me by Shri N.V. Nagarathnam. I have tentatively selected 10 important documents that, according to me, describe the structural analysis and design of the 45m dishes of the GMRT (see Section 5.2). Xerox copies of the technical notes included as introduction to the Computer output files of TCE have been made and will become part of a Technical Document (Part C). These technical notes along with the Detailed Design Engineering Notes essentially describe the specifications and brief results of the computer analysis of the structures of the 45m dishes, on which basis fabrication drawings were finalized by Dec. 1989.

Annexure A9 gives a list of 10 drawings giving computer model used by TCE for the analysis of DISHCRAD (see the introduction of that file given in Part C.).

From an almirah at NCRA in which copies of many drawings of the strctures of the GMRT are available, I have copied a list of 129 construction and erection drawings that was pasted on its door, (Annexure A10). This list needs revision as it does not give R number of the latest drawings. I have included it in this draft report so that a latest list giving final construction and erection drawings is prepared. It is likely to be available at the GMRT. I understand that the tracings are available at NCRA.

7 Automatic Stowlocking of the 45m Diameter Dishes of the GMRT

At present antennas are stowlocked by the ‘Telescope Observers’ if the wind velocity averaged over 1 minute exceeds 45 kmph in the wind metre that is mounted at the top of the water tank in the Central Electronics Building (private communication by NVN on 090509). In order to minimize stowlocking during gusty winds in the monsoon period, when highest wind due to the summer thunderstorms (squalls) do not occur, the stowlocking value of 50 kmph rather than 45 kmph averaged over a minute may be considered.

Safety of the GMRT antennas during the occurrence of the summer thunderstorm squalls with very heavy winds is very important, for which stowlocking minimizes any risk. The MSEB power gets disrupted often by the lightening striking LT and HT lines during the occurrence of severe thunderstorms and very high winds. Considering all these aspects it was decided about 10 years ago to install diesel generators at all the Y array sites (two 220 kVA sets already existed at the Central Array). I was very surprised to know a month ago that (i) the diesel generators (DG) are installed at only 6 of the 16 Y-array antennas and (ii) only 15 out of the 60 wind meters are operational at present, many due to electronic circuitry. This situation needs to be corrected with urgency before the end of this year (we are lucky that very high winds say > 130 kmph have not occurred at the GMRT antennas during the last 15 years). Even if DG sets are installed at all the Y-array antennas, the optical fibre communication and telemetry may get disrupted due to power failure. Nevertheless, considering the importance of minimum equipment and not depending on telescope operators, a suitable scheme for **automatic stowlocking** of the antennas needs to be developed.

Tentatively, I suggest as follows (a detailed scheme to be developed by the GMRT group at the earliest in my view): (a) Install reliable wind meters at all the 30 antennas (2 each) and make them operational. If required, modify their enclosures to ensure weather proofing; use rugged electronics. (b) As soon the 1-minute average value of the velocity measured by any of the two wind meters at any of the GMRT antennas becomes greater than 50 kmph, firstly a signal is sent by the associated electronics of the wind metre to the Servo system for stopping any tracking etc of that antenna, and then after one minute, a command is issued to the servo system for slewing that antenna towards the zenith and stowlocking it. (c) If the power to any one or more antennas is interrupted by the MSEB, diesel generators (DG) at the Central array and also remote stations of the Y-array are automatically switched on; (c) DG sets continue to remain ON if the wind velocity averaged over one minute exceeds 50 kmph, till the antenna gets stow locked; (d) If the wind velocity has a smaller value than 50 kmph, the DG gets switched out and could be put ON only by the telescope observer, if required, for the GMRT observations. Information concerning the operation of the DG sets (and if possible quantity of diesel remaining in the DG sets particularly for the Y array) should be brought to the Control Room. All the above requires a dedicated effort by the electrical and servo group over the next couple of months and installations at all the 30 antennas well before the next squall period of April 2010.

In my view its importance should not be overlooked as stowlocking of the large antennas of radio telescopes is routinely done world over (including at Ooty), in case of upcoming severe storm. At the sites of many radio telescopes, advanced information is available, e.g. at Ooty information about high winds gets available well in advance as cyclones hit coastal regions and move inward. For single radio telescopes, such as at Parkes or Jodrell Bank, weather predictions are also available well in advance. The situation at the GMRT is different as high winds occur suddenly during a thunderstorm and squall, often within 15 minutes. Hence automatic stowlocking was considered essential. As is documented elsewhere, a simple scheme based on batteries and contractors (rather than DG sets) was demonstrated on C4 antenna in 1994 by NVN and Hotakar, modified by BARC and approved by me in April 1995. Hotkar was not happy and worked on a Pulse width modulation scheme. I made an analysis of all the proposals in a 45 page technical document in May/June 1999 and recommended that the scheme of Hotkar be demonstrated and installed on all antennas. (I plan to document the above schemes in an internal technical report for the sake of history). Since Hotkar resigned soon after, the GMRT group decided to get diesel generators installed at all the Y-array sites. But the automatic stowlocking has not been implemented so far and that's why the present long Technical Report!

It is also quite important that the Servo system provides the required current to the elevation drive for slewing the antenna to zenith at a wind speed of 85 kmph. I reproduce my comments in my above mentioned report of May/June 1989: page 17: "It may be noted that from the last column of Table 2, page 19 (of that report) that the total current requirement for slewing the antennas at a wind speed of 80 kmph is 79 Amp. and at 85 kmph =87 Amp. However, in the present servo system the current limit has been set up as 35 Amp. for each motor equal to 70 Amp. for two motors. Further, since a bias of 10 amp is provided for the Counter-torque system, the actual current is only 35 + (35-10) = 60 Amp. This limit of 35 A was decided as a conservative value during erection. It is strongly recommended that this is changed to 48 Amp. So that the servo system can provide total current of 86A = (48 + 48 -10), and antennas could be stowloclked up to the time the wind velocity is below 85 kmph. "

It is also important that automatic stowlocking of antennas be tested on the weekly maintenance days, particularly during April to mid June and September (see Section 3 of this report for details). Testing may be done after switching off the electrical supply to all antennas and ensuring stowlocking using the common diesel generator at the central array and individual generator at each of the antennas. The test report may be sent to the scientist-in-charge of the GMRT and the Centre Director. A suitable check and countercheck procedure needs to be evolved regarding the safety aspects of the GMRT antennas.

A barometer in the control room may be useful. Further, I understand that equipment for detecting radio emission from distant thunderstorm of 10 or 20 km is now available. Indian Institute of Tropical Metrology (IITM) may be consulted. According to the Wikipedia, **signs of the up-coming squalls appear in the sky as follows:** shelf clouds and roll clouds are usually seen above the leading edge of a squall, also known as a **thunderstorm**'s gust front (see reference 14 of the section on Squalls in Wikipedia): **"from the time these low cloud features appear in the sky, one can expect a sudden increase in the wind in less than 15 minutes".**

According to the National Weather Service Forecast Office, Springfield, Missouri: Storm Spotter Online Training is described in http://www.crh.noaa.gov/sgf/?n=spotter_squall_lines

8 Summary of Suggestions and Recommendations for the Proposed Review of the Structural and Mechanical Design of the 45 m Dishes of the GMRT.

This section summarizes the recommendations made in Sections 2 to 5. I understand that NCRA has recently requested TCE to make a review of certain aspects of the structural and mechanical design of the 45 m dishes, particularly considering maintenance aspects, load at the focus and to take a fresh look regarding safety of the GMRT antennas in case of very high winds. Although the GMRT and TCE engineers would certainly look at all the aspects in detail, I summarize some suggestions (based on discussions earlier in this Report) **that may be considered but should not give rise to a bias.**

8.1 **DDEN-1 (v01)**: In the revised analysis, I recommend a value of Cd of 1.2 at $\theta = 0^0$ for the 10 mm x 10 mm x 0.55 mm mesh, 1.1 for the 15 mm x 15 mm x 0.55 mm mesh and 1.0 for the 20 mm x 20 mm x 0.55 mm mesh in the inner, middle and outer 1/3rd portions of the GMRT respectively, decreasing as $\cos^2\theta$ up to ~ 0.2 at 73^0 and remaining 0.2 up to 90^0 (Curves marked as D, E, and F in Fig. 2 of this Report). This recommendation is consistent with recent literature summarized by Swarup (2007). During 1987-89, TCE had used Cd = 1.42 for normal direction and 0.4 for 90^0 (**Fig. 2**). In my rough estimate, using the above lower values of Cd as mentioned above, stresses on the structural members of the GMRT dishes may get decreased appreciably, say by about 5 to 7 %.

8.2 **DDEN-2 and 3 (v02, v03):** These describe forces on the triangular frames of the structural members of the 45m dish, considering wind loading on all the projected area of individual members in the direction of the wind. An estimate is made of shielding by front members, as per Table 32 of IS: 875 (1987). However, guideline for shielding factors for a parabolic dish is not given in IS: 875. A detailed consideration of the above aspects was made by TCE during 1988-1989 and shielding factors were derived for the case of the zenith and other orientation of the dish. During the review, TCE may perhaps re-examine the assumptions made concerning the shielding factors. As noted earlier, TIFR requested Prof. Prem Krishna, a distinguished wind loading expert of the University of Roorkee to get wind tunnel tests done on a suitably scaled model of about 1.5 m diameter of the 45m dish. It should be noted that the wind tunnel tests provide values overall forces and moments on a parabolic dish but do not provide wind loading on individual sub-sections (triangular frames) of the dish. Perhaps, the recent availability of Computer Fluid Dynamics (CFD) analysis, as is being done by several groups in India, may be useful to assess the wind loading on the structures of the 45m dish, in order to find out whether the GMRT antennas are safe for much higher winds say 41 m/s (~ 148 kmph) than the value of 37 m/s (133 kmph) considered in 1989.

8.3 **DDEN-4 (v04):** It would be useful to find maximum value of the wind velocity at which there would not be damage to the 45m dish. In my view one should particularly look carefully at the following sub-structures and identify and *separately list* structural members with stress close to or a bit higher than the "normal permissible stress" (equivalent) as per column 3 of Table 1 of DDEN TCE-G18-01-153 V-05.

8.3.1 quadripod members, not only at the bottom joints near the prfs, but also at the top where dead loads also produce considerable stress (weight of stools and RF boxes can perhaps be perhaps; one may consider changing stools made of stainless steel or Aluminium (present MS stools get badly rusted, as their painting is difficult, which may trigger rusting of the nearby steel members of the quadripod). The dead loads and wind loads of all the old and proposed new feeds and the new drive system will be considered in the review by TCE.

8.3.2 Stress in the structural members near the joints of the quadripod to the parabolic frames (prfs) and also prfs to the hub, particularly if the hub joint is considered clamped;

8.3.3 Stress at the joints of the rim to the prf.

8.4 **DDEN 11**: As described in DDEN 11, v11 (1989), the structural space frame of the GMRT dishes was analyzed by TCE as pin-jointed space frame. The computed stresses were multiplied by TCE using increase factors derived in DDEN V-11 to obtain the total stress, called ‘stress factor’ as a fraction of the yield stress fy. TCE also analyzed the space frame as rigid jointed space frame to obtain axial stresses and bending moment, and thus calculate the ‘stress factor’ for all the structural members of the dish. From a limited study of the computer outputs of DISHCRAD and RIGIDISH, I find that the ‘stress factors’ are generally lower in the latter case by about 5% to 15% for the main members of the triangular trusses and ~ 30% for the struts and bracings (Section 5.4.2). ***The major question is as to what are applicable constraints to be considered for displacements and rotations of tubular members of trusses in which all joints are welded, in order to take care of rigidity, according to the IS and international codes and practices.***

8.5 **The Drive System of the 45 m parabolic dishes. I**t may be worthwhile to review the safety of the gear boxes and of the pins of the bull gear in case the antenna does not get stowlocked and winds may exceed 140 kmph; also bolts of the ring supporting the slew ring to the concrete tower. Required torque value of the brakes, particularly for the elevation drive in case the 45m dish does not get stowlocked.

I understand that TCE is planning to analyze maximum stresses in the structural members using the STAADS software. Last year I was closely associated in the structural analysis of a modified 12m Preloaded parabolic dish, PPD, (stiff bracings added to the original design and also Al sheets up to 8m) done by an M.Tech student of MIT, Pune and Prof. Mridula Kulkarni of MIT. We used both ANSYS and STAADS. Both gave almost identical results but STAADS was very much faster and allowed graphical presentations in colour of displacements of the structural members of the PPD. In fact once a model is made, I could myself run STAADS on my laptop readily. It would be useful if stresses can also be summarized in colour across the dish (that could not be tried by us as the student ran out of time!)

9 Comments by Shri Tapde & Shri Yogi on the draft report

Shri Tapde and Shri Yogi have given detailed comments on the draft of this report that was sent to them and several senior scientists of NCRA (see Attachment.Part D giving copies of their comments and my response to Shri Yogi) A brief summary of their comments is given in Sections 8.1 and 8.2.

9.1 Summary of comments by Shri Tapde:

(1) repairs should be taken up as soon as possible, so that further deterioration does not occur.
(2) Shri Tapde has also commented regarding (a) wind velocity, revision of design value, (b) stowing the dishes to zenith
(c) Cd values for mesh and (d) focus loads/ feed drive. Please see Part D. *** I agree with his valuable comments.***

9.2 Summary of Comments by Shri Yogi:

(1). All computer outputs (design reports) documents pertaining to GMRT antennas, available at TCE Bangalore office were sent to NCRA in 2005 just before retirement of MKSY.

(2) All comments on the draft report are therefore based on MKSY's recollection of the GMRT work between 1987 to 1989 and material sent as attachments sent by GS.

(3) Identification of **10 reports listed in Part-C** appears to be correct.

(4a) Shri Yogi commented that the CFD analysis for the entire dish may require considerable work and should be done by an experienced person with a proven software and the work should be thoroughly reviewed by an independent expert before results are used for further structural and mechanical analysis and design activity.(see my (swarup) response given in Part D: I had suggested CFD analysis primarily to determine the wind loading on the parabolic frames in the zenith position of the dish for which case it is not practical to determine shielding by the front members to the back side members as the geometry is quite complicated and it would be worthwhile to check the shielding factors considered by Shri Yogi. (4b) STTAD would provide realistic results including consideration of welded structures but would require careful consideration of constraints at all the welded or bolted joints.

Specific requirements for design of welded tubular connections (statically or cyclically loaded) are given in Part-D of Section-2 of the Structural Welding Code – Steel (American Welding Society Code of Practice AWS D1.1/D1.1M:2002). Tubular members with welded connections could be checked using guidelines given in the Structural Welding Code.

(4c) Stress ratio given in the computer outputs of 1989/1990 refers to fraction of yield strength.

(4d) Safety aspects of all members of structure (not only quadripod members) should be highlighted.If a cradle member near the elevation bearing at the top of the cradle structure fails, the entire dish could come crashing down.

10 Discussions and Conclusions

During 1988 and 1989, Shri M.K.S. Yogi and colleagues of M/s Tata Consulting Engineers (TCE) made an extensive study of various design parameters that were required for optimization of the structural design of the 45 m parabolic dishes of the GMRT. Several preliminary, progressive and final reports were given to TIFR. Several alternatives were discussed (eg. rope truss system shown in Annexure A11) and appropriate choices made considering practical aspects. Several computer outputs giving analysis of the structural were also given and finally detailed drawings were released for the construction and erection of the antennas to two selected engineering firms. TIFR also made some preliminary design studies, including discussions with international experts. These documents are scattered in several almirahs and filing cabinets at NCRA and GMRT. Over the last few weeks, I have searched and sorted out several important documents and computer outputs that were the basis of the final structural design of the GMRT antennas. Brief discussion of several of these documents and computer outputs is given in this Report. A list of the relevant documents is given in Section 5.2. This Report will be modified after correspondence with Shri Yogi and Shri Tapde. A separate report will summarize the mechanical design and relevant documents.

One of my main objectives for this report is to review safety considerations of the GMRT 45 m dishes in case of very high winds that occur in the Pune region, particularly during the summer and autumn months as a result of the squalls accompanied by thunderstorm. For this purpose I have considered four major input specifications that, according to my understanding, determine maximum stress in the structural members at the assumed maximum design wind velocity. My purpose is to review the assumptions and specifications made and to recheck stresses induced in the structural members of the 45m dishes using modern computer software. It would be useful to know the stresses induced for the wind velocity of 37 m/s, 39 m/s and 41 m/s as a fraction of the permissible stress with respect to the yield strength of the steel members of the 45 m dishes.

Although the structural design of the GMRT antennas was based on many parameters, I have highlighted in this report four major input specifications. These are: (a) load of antenna feeds near the focus of each of the 45 m dish, (b) maximum wind velocity at the GMRT site that is likely to occur in the design life of the GMRT antennas (so called Survival velocity), (c) wind loads on the wire mesh based on assumed drag factor; wind load on the main structural members that depend on assumptions of shielding by the windward members to other members of triangular trusses of the antennas (shielding parameters) and (d) maximum allowable stress in the structural members at survival velocity; the computer design of the 45 m dishes was based on pin-joint assumptions of all joints but since all the tubular members of the 45m dishes are welded, stress increase factors were assumed by TCE based on a sample study and a final DISHCRAD analysis formed the basis of the structural design of the 45m dish; separate computer analysis were made for the cradle and Yoke. The design of the concrete towers was done by the civil engineering group of BARC.

Recently NCRA has requested TCE to make a review of certain aspects of the structural and mechanical design of the 45 m dishes, considering maintenance aspects, load at the focus and to take a fresh look regarding safety of the GMRT antennas in case of very high winds. Since I was closely associated in the discussions and final selection by TCE of several important input specifications, I have taken the liberty to make certain suggestions for the review based on discussions given in Sections 2 to 5 and as summarized in Section 7. During 1988 and 1989, TCE made a commendable job in developing special computer routines. It would be useful to review the design using modern software for structural design. Such reviews have been done for some other telescopes in the world, e.g. a major review of the design of the 25 m dishes of the Westerbork antennas designed in 1971 was done about 10 years ago and some corrections made.

11 Acknowledgment

The successful design, construction and operation of the Giant Metrewave Radio telescope is a result of enthusiastic and dedicated efforts by a large number of scientists, engineers,

technicians, administrators and other workers of several organizations and contractors. Over 20 engineers and many draughtsman of M/s Tata Consulting Engineers (TCE) made extraordinary contributions to the innovative and economical design of the GMRT. I recall particularly the great enthusiasm and important contributions by Shri D. Satyanarayan, particularly during the feasibility studies of the Giant Equatorial Radio Telescope (GERT) that later became the GMRT! Shri S. C. Tapde, I and some colleagues of NCRA interacted closely with TCE regarding the design of the structural and mechanical systems of the GMRT, with Tapde taking close interest in the mechanical design and I a bit more in the structural design, particularly that concerning the parabolic dish. As the former Project Director, I thank all who contributed to the design and construction of the GMRT.

12 References

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13 Figure Captions

Fig.1: (Section 3): Extreme wind plot by Kapahi and Swarup (1986) based on maximum wind velocities recorded at Pune in each of the 35 years from 1948 to 1982. The plot was made using the procedure given by Narsimha and Shrinivas (1983).

Fig. 2: Drag Coefficients for wire-meshes of different solidities: Curve 5 was used by TCE for the design of the GMRT antennas for all the 3 sizes of wiremesh; Curves A. B and C give NAL measurements for the wiremesh sizes given in the Table at the top; Curves D, E, and F give values recommended in this Report for the proposed review by TCE.

Fig.3: Variation of Cd (drag), Cl (lift) and resultant Cf with angle of incidence from the normal to the 6 x6 mm wire mesh, as measured by SERC (2008) in their wind tunnel at Chennai. Surprisingly SERC finds the value of Cd = 1.0 at normal to the mesh!!

Fig. 4: Sectional elevation of the 45m parabolic dish (Swarup et al. 1991).

Fig. 5: Front and rear schematic of the 45m parabolic dish (Swarup et al. 1991).

Fig. 6: A section of the dish, illustrating the SMART concept (Swarup et al. 1991).

14 Annexures

Annexure A1: “Note to all concerned persons” with copies to senior persons at NCRA/GMRT giving the maximum values of the wind in each year from 1948 to 1990.

Annexure A2: Calculated Risk for the assumed maximum wind (survival) for a return period of T years (see Table 2.5 of Sachs (1978)) reproduced below.

Annexure A3: Basic wind data recommended for Pune by Lashmanan et al. (2009).

Annexure A4: Cd values for various sizes of mesh of low solidity reproduced from the paper by Swarup (2007), with some additional data added.

Annexure A5 A brief comparison of the stress ratio values in the computer outputs of DISHCRAD (in blue) and RIGIDISH (red) by TCE, for some typical cases with relatively high stress factors (made by the Author). It is seen that the stresses are lower for the RIGIDISH case by 5 to 15%. For bracings and struts stress ratio are more than 30% lower for RIGIDISH.

Annexure A6: R.M.S. Surface Errors in mm with respect to the best fit paraboloid of the 45m dishes for 6 positions from horizon to zenith. Displacement of the focus is less than 5 mm in x, y and z direction. (details in document C7).

Annexure A7 (4 pages): gives few results from the computer analysis of YOKE (document C4), regarding forces and moments at the elevation and azimuth bearings.

Annexure A8 (2 pages): gives few results from the computer analysis of YOKE-Stiffness (document C5), regarding Masses, Moments of Inertia, deflections of Yoke Structure (mm),stiffness and natural frequencies of the Yoke.

Annexure A9: List of Drawings including General Arrangement and Computer Models (9drawings).

Annexure A10: List of 129 drawings of structural and mechanical parts of the 45m dishes of the GMRT for fabrication and erection.

============================== **Attachment** ==============================

15 Part C: gives copies of the 11 DDE notes and of design basis documented by TCE for computer analysis of various parts of the 45m dishes.

C0: Eleven “Detailed Engineering Design Notes (DDE Notes)” by TCE giving design basis for the 45 m dishes of the GMRT.
C1: TCE.G18/DR/CAL/153-DISHCRAD, dated 18/20 Feb 1990 (final **space truss** pin-joint analysis of the 45 m dish, giving input data, displacements and stress ratios).
C2: TCE.G18/DR/CAL/153-CRADLE, dated 19 Feb 1990 (final analysis of the cradle).
C3: TCE.G18/DR/CAL/153-RIGIDISH” dated April 23 and 28 1990 (the structure of 45 m dishes is considered as a rigid space frame).
C4: TCE.G18/DR/CAL/153-YOKE-01-R1 dated 07-03-90, gives stresses, displacements and forces and moments at the elevation and azimuth bearings)
C5: TCE.G18/DR/CAL/153-YOKE-STIFFNESS-01-R1 dated 18-07-91; (as above and also natural frequencies).
C6: TCE.G18/DR/CAL/153-RMSBIAS dated 22-06-90; (rms errors if initial coordinates of the paraboloid are biased to various zenith angles of the 45 m dish).
C7: TCE.G18/DR/CAL/153-RMSERR dated 22-06-90; (displacements of best fit parabola and rms errors).
C8: TCE.G18/DR/CAL/153-DISHERECTION dated 10-04-91.
C9: TCE.G18/DR/CAL/153-RECT dated 05-07-1990, “Analysis and design of the reinforced concrete tower”

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16 PART D. Comments by Shri Tapde, Shri Yogi and Dr. Gomathinayagam

D.1: Comments by Shri Tapde:

Dear Prof Swarup

Hats off to you for your perseverance in collating all the information on design of 45m dishes and for the concern for their “health”. While we wish them a very long life, booster shots may have to be administered periodically, after thorough health check. Certain “dos’ and “don'ts” have also to be recommended by the “doctor” (you) and observed by the “caretakers” (new generation), so that “undertakers” have no chance.

On the serious side, repairs should be taken up as soon as possible, so that further deterioration does not occur. For the "refurbishing" with a denser mesh, we should first reconfirm all what was done by tce during the design phase and then systematically choose to introduce changes, preferably one by one "on paper" first. Once all concerned are convinced of the changes, we should take them physically. My comments on the subject are as follows:

1. wind velocity, revision of design value

the concerns raised by you will make us revise the figure to a higher value, which will grossly imply higher stresses and may eat away the leeway we may have with lower Cd values for the wire meshes.** Response by GS: my recommendation is simply to know those members that would have higher stress factors for 39m/s and 41 m/s compared to the value of 37 m/s considered in the design made during 1987-89.**

2. stowing the dishes to zenith

as we had chosen the gear boxes for safe operation up to 80 kmph wind torques, the starting of stowing operation should start before the wind could build up to 80 kmph. If the stowing operation is "guaranteed" to start "every-time", may be the dish would have reached a position above 45 deg elevation (the dish may be there to begin with) from where onwards the drive torques required may start falling and allow the gear boxes to safely stow the dish to zenith. However, this is quite "subjective", the judgement of the observer being the deciding force. We have already seen by analysis the safety of the dish in any orientation in elevation, which together with "conservative" approach by mr yogi has so far been a "blessing" in cases when the dish has not been put to stow position in higher winds.**I agree**

3**. Cd values for mesh**

Your recommendation of values to be used during recheck by tce of the gmrt dish structure is well argued in the report. However, the gain here may be lost in newly specified higher "design" wind velocity. 1.42 to 1.2 gives a factor of 1.167, under root of which is 1.08, giving 8% increase in wind velocity. If we take 1.42 to 1, under root of which is 1.19, an increase of 19% with this only we could think of finer mesh in inner one third area. We may be able to put 6x6 mm mesh in the centre hub region, if not in the total inner one third area of the dish, without any risk, but I am not sure how much benefit it will give in the 1.4 ghz operation.

4. focus loads/ feed drive

Lots of changes have been made in feeds/stools/python etc. only one positive thing has happened that the new cable wrap (python) is very sleek and light weight. However, the changes in feed sizes, shapes and masses, I am not well aware of. For the feed drive, you mean "helical gears" by "involute gears" ? if "self locking"is dispensed with (for gear boxes), sleek planetary gear boxes are available in one fifth the mass. In that case one may have to resort to a "stow pin" for locking the turret in one of the 90 deg positions *** my recommendation to use DC motors with brakes and "helical gears" (I wrote involute wrongly) is the purpose of minimizing backlash that seriously affects pointing errors particularly for higher frequencies.***

I hope the above is worth taking note of.

Regards

Suresh tapde

D.2. Comments by Shri M. K. S. Yogi of TCE (who was principally responsible for the structural design of the 45 m dishes), and reply by G. Swarup in *……*****

3-7-2009

Response to queries given in the last paragraph of Prof. G Swarup's e-mail dated 1-7-2009

References : swarupall.pdf and GMRT-structuralDesign-draft(070609).doc

1. All computer outputs (design reports) documents pertaining to GMRT antennas, available at TCE Bangalore office were sent to NCRA in 2005 just before retirement of MKSY. One set of DDEN-1 to DDEN-11 for GMRT and a report on design of tower for painting GMRT antennas, available at MKSY's residence, were given to TCE (Mr. Pendse) in 2009. All documents pertaining to 12m PPD were given to RRI. This was done to ensure that antenna material available with MKSY is available at the required places and not lost during periodic paper clearing effort at MKSY's residence. At the moment, MKSY does not have any hard copies of material related to GMRT or the 12m PPD antennas.

****Thanks. Noted****

2. All comments on the draft report are therefore based on MKSY's recollection of the GMRT work between 1987 to 1989 and material sent as attachments sent by GS.

3. 10 reports listed in Part-C at the end of the draft report :

Identification of the reports appears to be correct.

I am glad.

4. **(a) CFD analysis will give a better estimate of the shielding of the members** :

Mr. Tapde will be able to provide an answer to this query since he was associated with the CFD work for the 32m DSN antenna.

Mr. Lakshmnan of SERC will be able to provide another reliable answer since he is an expert in wind tunnel studies and has done work on wind speed estimates based on meteorological data. He will be able to answer questions about reliability of CFD results for ground based civil engineering structures with changing orientation subject to wind in various directions and winds of various speeds with gusting.

For instance, the overall wind loads and moments at elevation axis level obtained from a wind tunnel study do not help a structural engineer in design of members of the structure. Wind loads at joints of the structure are required to complete a structural analysis to obtain member forces for design of the members of the structure.

Computational fluid dynamics (CFD) analysis could possibly be used to estimate wind loads on the GMRT structure. MKSY has no experience in CFD analysis of civil engineering structures with changing orientation subject to wind in various directions and winds of various speeds with gusting.

One should have a clear idea of information obtained from CFD analysis work (eg. Do you get load in kilograms in x, y and z directions at all joints in the structure to do a subsequent structural analysis ? Is structural analysis included within the CFD analysis to give member forces for design of members?). The information from the CFD analysis should be such that it can be used for analysis and design of the structure. One should take a decision on CFD analysis after getting cost estimates for the CFD work. However, based on a slight familiarity with fluid mechanics, some comments are given below.

CFD model could include all components like wires of reflector mesh, turnbuckles, members of the structure, adjustment studs, wire ropes, fixed and moving angles for supporting wire mesh panels between adjustment studs, different drive systems (feed, elevation & azimuth), elevation and feed drive gears, counterweight, yoke structure, concrete tower, platforms, ladders etc. All components should be modeled at their respective locations so that shielding effects are captured in the CFD analysis results properly. The number of components that could be considered to determine the wind loads is vast. After all components are modeled in a satisfactory manner (with realistic approximations and assumptions, as required), a CFD analysis could be done for several wind directions for each position of the antenna. Hopefully, all shielding effects (between individual wires of the mesh, between wires of the reflector mesh and members of the structure, between drive systems and members of the structure, between concrete tower and dish in a particular position, etc.) and ground effects between dish, tower and ground surface will be considered automatically and properly and reliable values of wind loads will be obtained with the click of a key on the keyboard. One possibly need not bother about whether drag coefficient for mesh should be 1.2 or 1.44 for a particular orientation of the mesh (for a particular orientation of the dish) with respect to the wind direction since all this is considered properly in the CFD analysis work.

The magnitude of drag coefficient for a SS wire or MS pipe or a bluff body like the drive motor (and therefore the magnitude of wind load on it) depends on Reynolds Number for the wind flow. The Reynolds Number depends on the typicl dimension of the item (e g. diameter of the wire or pipe) and the wind flow velocity it is subjected to. CFD analysis could be done for different wind velocities (with associated gust effect) for a dish position to estimate consolidated C_D, C_L & C_M values for that wind velocity (a) at the centre of the elevation axis for design of the elevation drive system (b) at the azimuth bearing level for design of the azimuth drive system and (c) at the ground level for design of the foundation system.

All CFD work should be done by an experienced person with proven software and the work should be thoroughly reviewed by an independent expert before results are used for further structural and mechanical analysis and design activity.

** Thanks for your detailed comments. I agree that CFD analysis would require a careful pre-discussion before launching it. I did not consider CFD analysis for the entire dish that may not be relevant at present as antennas are all designed and the main question is whether the structure would be safe for 39m/s or 41m/s.

However, I may add that I Suggested CFD analysis mainly to wind drag factor or the shielding factor carefully evaluated by you for the PARABOLIC FRAMES (a) for wind perpendicular to the dish, for which case CFD analysis is likely to validate shielding factor calculated by you, being a relatively simple geometry, and (b) for the zenith case in which case in which case the geometry is quite complicated and it would be worthwhile to check the shielding factor considered by you.**

4(b) **Pin-joint analysis and rigid jointed analysis work by TCE :**

Pin jointed analysis (with stress increase factors for joint rigidity used at the design stage) is not required because STTAD SW is available. STAAD SW has facility to specify member end releases. Structural analysis should be done for a realistic scenario of member end releases and members designed for a realistic set of member forces and moments.

TCE should examine how each member is connected at its ends. Is the member welded or bolted? TCE should then decide whether (a) the end joints for the member joint are fully rigid (no member end releases at its two ends) (b) the end joints are partially rigid (assign appropriate end releases for the member at its two ends) (c) the end joints are pinned (assign moment releases for the member at its two ends).

RMS surface errors and beam pointing errors should be determined for a realistic scenario of member end releases.

** I am glad to note that STTAD would provide realistic results that can be compared with your carefully considered stresses.**

4 (c) **Stress ratio refers to fraction of yield strength :**

Examples 1 & 2 are given below to explain what is meant by stress ratio.

Allowable stress for member = a fraction of the yield strength.

Stress ratio = actual stress in member / allowable stress for member

Example -1 : Tensile stress

Yield stress in tension = f_y = 240 N/mm^2

Allowable stress in pure tension = 0.6 f_y = 144 N/mm^2

Actual member stress - tension (assumed) = = 96 N/mm^2

Stress ratio in tension = 96/144 = 0.66

Example -2 : Compressive stress

Yield stress in compression = f_y = 240 N/mm^2

Maximum allowable stress in pure compression = 0.6 f_y = 144 N/mm^2

Actual allowable stress in compression for slender member = $< 0.6 f_y$ = 100 N/mm^2

Slenderness ratio = 78

Actual member stress - compression (assumed) = 96 N/mm^2

Stress ratio in compression = 96/100 = 0.96

Formulae for stress ratio for members subjected to combined stresses (compression and bending or tension and bending) are more complex. Equivalent stress is one of the cases of combined stress (eg. tension, shear and bending).

** Thanks for your clarifications. I note your clarification that the values tabulated in your computer outputs are (I had assumed the same but wanted confirmation): Stress ratio = actual stress in member / allowable stress for member. **

4 (d) safety aspect of quadripod

Safety aspects of all members of structure (not only quadripod members) should be highlighted. If a cradle member near the elevation bearing at the top of the cradle structure fails, the entire dish could come crashing down to the ground. If a PRF member fails, there could be a progressive failure of the entire dish.

** Thanks for highlighting the safety of the supports of the dish at the elevation bearings. As I recall that the elev. bearing was selected on the advice of Shri Tapde with a relatively high safety value so that the shaft may not fail but the elev. Shaft is supported on **forged mounts** that the contactors may have not supplied with sufficient safety factors in spite of our rigourous inspections.

Nevertheless, I am really concerned regarding the safety of the quadripod and it needs to be done urgently as new feeds are planned to be installed over the next couple of years and their weight and wind loads need to be determined. As I wrote in my document that the loads that I gave you in 1988 were based on our preliminary design of the feeds that got frozen only by 1991 and 1992.**

A structural analysis with realistic releases at member ends should be done using STAAD SW before checking safety aspects of all members of the structure.

Specific requirements for design of welded tubular connections (statically or cyclically loaded) are given in Part-D of Section-2 of the Structural Welding Code – Steel (American Welding Society - Code of Practice AWS D1.1/D1.1M:2002). Tubular members with welded connections could be checked using guidelines given in the Structural Welding Code.

noted

D3. Correspondence with Dr. Gomathinayagam, former scientist of Structural Engineering Research Centre (SERC), Chennai

Executive Director <ed@cwet.res.in>
reply-to ed@cwet.res.in
to Govind Swarup <gswarup29@gmail.com>
ccgomsluft@gmail.com

dateWed, Jul 22, 2009 at 12:39 AM
subjectRe: Fwd: Basic Wind speed map of India- Your article in Current Science.
mailed-bycwet.res.in

Dear Dr.Govind Swarup,

First of all I thank you very much for your interest in the article which I had worked during my stay with wind Engineering at SERC.

During 2007 I happened to be one of the team members who was involved in some wind tunnel studies. Coming to specific answers to paras, 3 , 4, 5, please bear with my answers for the time being since Dr.Lakshmanan is in USA, and I am unable to run the programs which I developed in SERC.

The difference is due to the longer years of data at Pune (38years as against 14 for the Pune(A)).

The threshold was not uniformly 50kmph for all stations, it was given for the example station of Madras. For Pune it is 0.65 of ExtremeP (Table-1).For suggesting the basic wind speed map the values derived with longer years was adopted for reasons of statistical accuracy. (Extreme peak is determined as(mean+3 times std) from raw data and upcrossing peaks data.

Since the IS875 follows 3-s gust as stanard for basic wind speed the averaging time correction of (1.16). We suggest no changes in BASIC WIND SPEED of PUNE for structural designs.

I apologize for the inadvertant column shifting in two stations OZAR and PUNE. I shall send after I locate the table from my old back up. Extreme I have defined in para 3 above. Wmax isthe highest recorded value in the 38 year time series.You may please notice it is lower for Pune(A) as expected. Obviously,Wmax cannot be rational for design. It is given to give the details of the records.

To summarise I would like to place on record the excellent data maintained by IMD and the cooperation of IMD in selling the entire data to SERC for this study. However lack of long term data is not a problem in India alone it is the same with most of the developed countries as well, for the extreme value analysis.

thank you very much for your interaction ,

with best regards,

Dr. S.Gomathinayagam
Exe. director/ CWET

Show quoted text

Dear Dr Gomathinayagam

1. I read your article in Current Science of 10 April 2009 regarding "Basic Wind speed map of India with long term hourly wind data" with great interest. Dr Lakshmanan, you and your colleagues have done a very valuable and extensive analysis and I congratulate all of you.

2. Although you are very busy, we would greatly appreciate your comments on my queries given in Paras 3, 4 and 5 below at your earliest convenience.We are now reviewing the design and safety (against high winds) of the 30 parabolic dish antennas of 45m diameter of the Giant Metrewave radio Telescope located about 60 km north of Pune, that was built about 15 years ago. It is being used for exploring the radio Universe. As you would appreciate that the design of large parabolic dishes and its safety is critically dependent on the assumed basic wind speed (Vb). Its design was

optimized 18 year ago. *It is the largest radio telescope in the world operating at long wavelengths. It is an instrument primarily for basic research.*

3. We were surprised to see in your article a 33% higher revised basic speed (Vbr) for the "Pune (A) Lohagaon" than that for "Pune 2" , before the threshold wind of 50 kmph applied by you, and 19% higher after the threshold. Further for the latter case, you derive Vbr for "Pune 2" as 42 m/s and 50 m/s for "Pune (A) Lohagaon". These are very much higher than the IS 875 value of Vb being 39 m/s. Even if consider Pune to be located in Category 3 and "Pune (A) Lohagaon" in Category 2, the values for the latter should have been only 10% higher. GMRT is located in a Category 2 landscape.

4. Basic wind speed as per para 2 of IS 875 is " for a 50 year return period". In your Table 2 you have given Vbr as "revised basic speed" but you have given about 16% lower values for "Wind speed with T = 50 years". Is it because of your remark on page 917 "based on discussions with IMD, this gust wind in general is the wind sustained over 1-2 minute duration".* Please comment as to which value of Vb should be used for design check of the GMRT antennas, Vbr before the threshold or after threshold or corresponding values given in column titled "Wind speed with T = 50 years"?*
5. In Table 2 of your paper, regarding "Pune 2" there seems to be misprint. Perhaps whole row should be shifted by one column. I would appreciate for your sending a xerox copy of corrected Table 2 to avoid confusion. If it is not too much trouble, please also explain the symbols, Wmax (kmph) and Extreme (kmph) in Table 1.

6. I may add that I am well familiar with the risk factors for a structure with different return period of winds; e.g. a 50 year return period implies 63% chance of failure in 50 years. For a radio telescope consisting of a parabolic dish, this risk is minimized by stowlocking the antenna in zenith position that experiences lower wind loads.

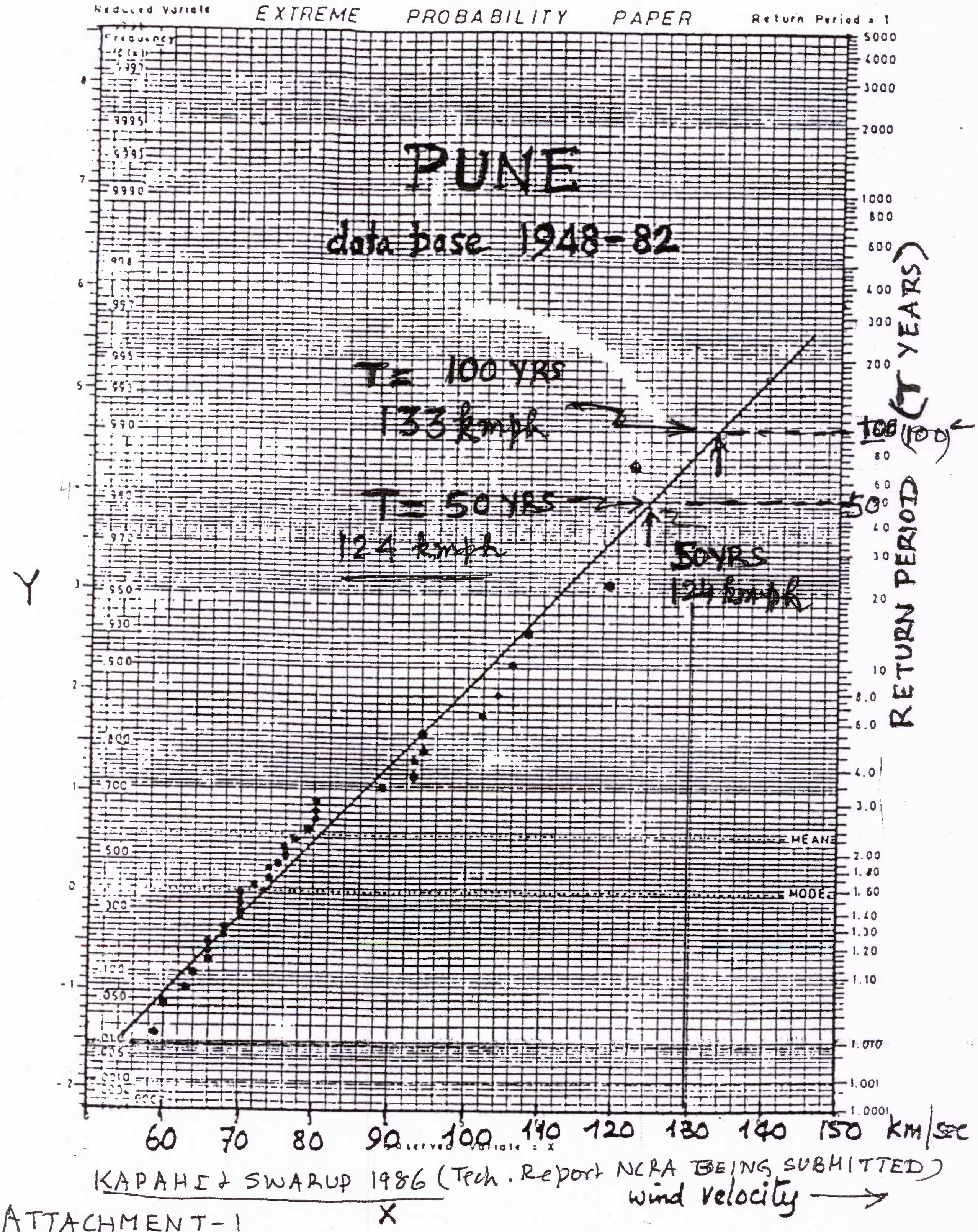
7. GMRT has been built and is being operated by the National Centre of Radio Astrophysics of the Tata Institute of Fundamental research for fundamental research in the field of radio astronomy. In 1986, we collected from the IMD, values of highest winds in each of the previous 35 years at Pune and made an extreme value analysis using the report of Narsimha and Shrinivas (1983), similar to that given in Sachs (1978). We also talked to Mr M.C. Sarma of IMD and got his 1985 report. Therefore we used 5% lower value for the wind velocity than the IS875 value of 39 m/s. We now plan to consider safety of the GMRT antennas considering recent analysis of wind data by your group. We would be very grateful to you for clarifications.

Govind Swarup

J

FIG.1

Fig.1: (Section 3): Extreme wind plot by Kapahi and Swarup (1986) based on maximum wind velocities recorded at Pune in each of the 35 years from 1948 to 1982. The plot was made using the procedure given by Narsimha and Shrinivas (1983).



KAPAHI & SWARUP 1986 (Tech. Report NCRA BEING SUBMITTED)

ATTACHMENT-1

EXTREME WIND PLOT FOR 35 YEARS AT PUNE
BASED ON MAXIMUM WIND MEASURED AT PUNE
FROM 1948-1982 (~~[illegible] BA~~ REF. Narsimha & Shrinivas 1983 also Sadhana)
FIG.2.

ATTACHMENT 4

CURVE	DETAILS		WIRE SPACING (mm)	WIRE DIA (mm)	WIRE SPACING/DIA RATIO	RATIO Solidity
5	DESIGN CURVE TO BE USED FOR DETAILED DESIGN		15	1.40	11	0.178
A A*	NAL RESULTS	REF-2 & 3	12	0.55	22	0.087
B B*	NAL RESULTS	REF-2 & 3	15	0.55	27	0.071
C C*	NAL RESULTS	REF-2 & 3	20	0.55	36	0.053

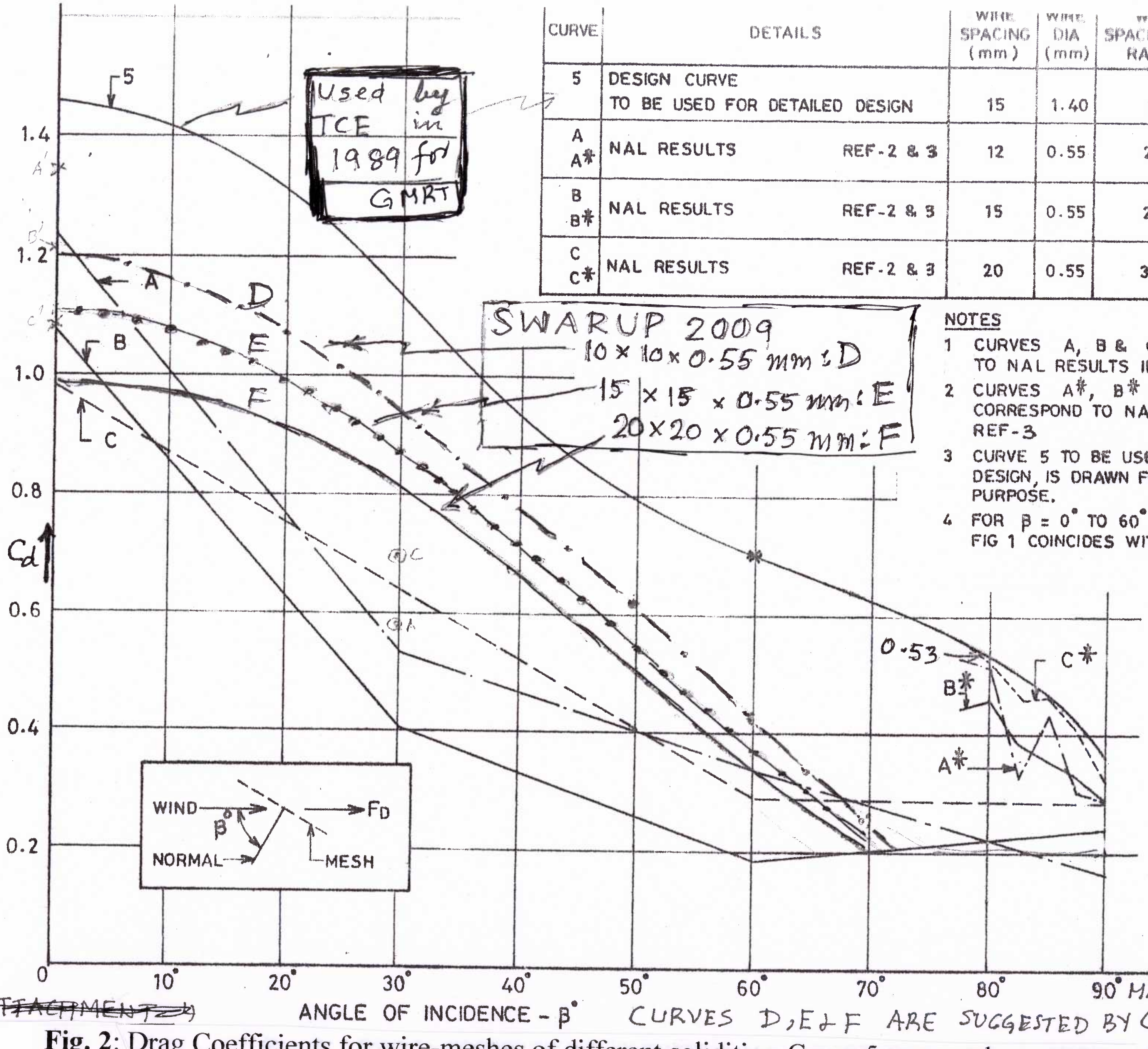
NOTES

1 CURVES A, B & C CORRESPOND TO NAL RESULTS IN REF-2.

2 CURVES A*, B* & C* CORRESPOND TO NAL RESULTS IN REF-3

3 CURVE 5 TO BE USED FOR DETAILED DESIGN, IS DRAWN FOR COMPARISON PURPOSE.

4 FOR β = 0° TO 60°, CURVE 3 OF FIG 1 COINCIDES WITH CURVE 5.



MAY 2009

CURVES D, E & F ARE SUGGESTED BY G SWARUP May 09

CURVE

Fig. 2: Drag Coefficients for wire-meshes of different solidities: Curve 5 was used by TCE for the design of the GMRT antennas for all the 3 sizes of wiremesh; Curves A. B and C give NAL measurements for the wiremesh sizes given in the Table at the top; Curves D, E, and F give values recommended in this Report for the proposed review by TCE.

FIG. 2

(J)

FIG. 3 ~~ATTACHMENT~~ 6 A6

FIG. 3

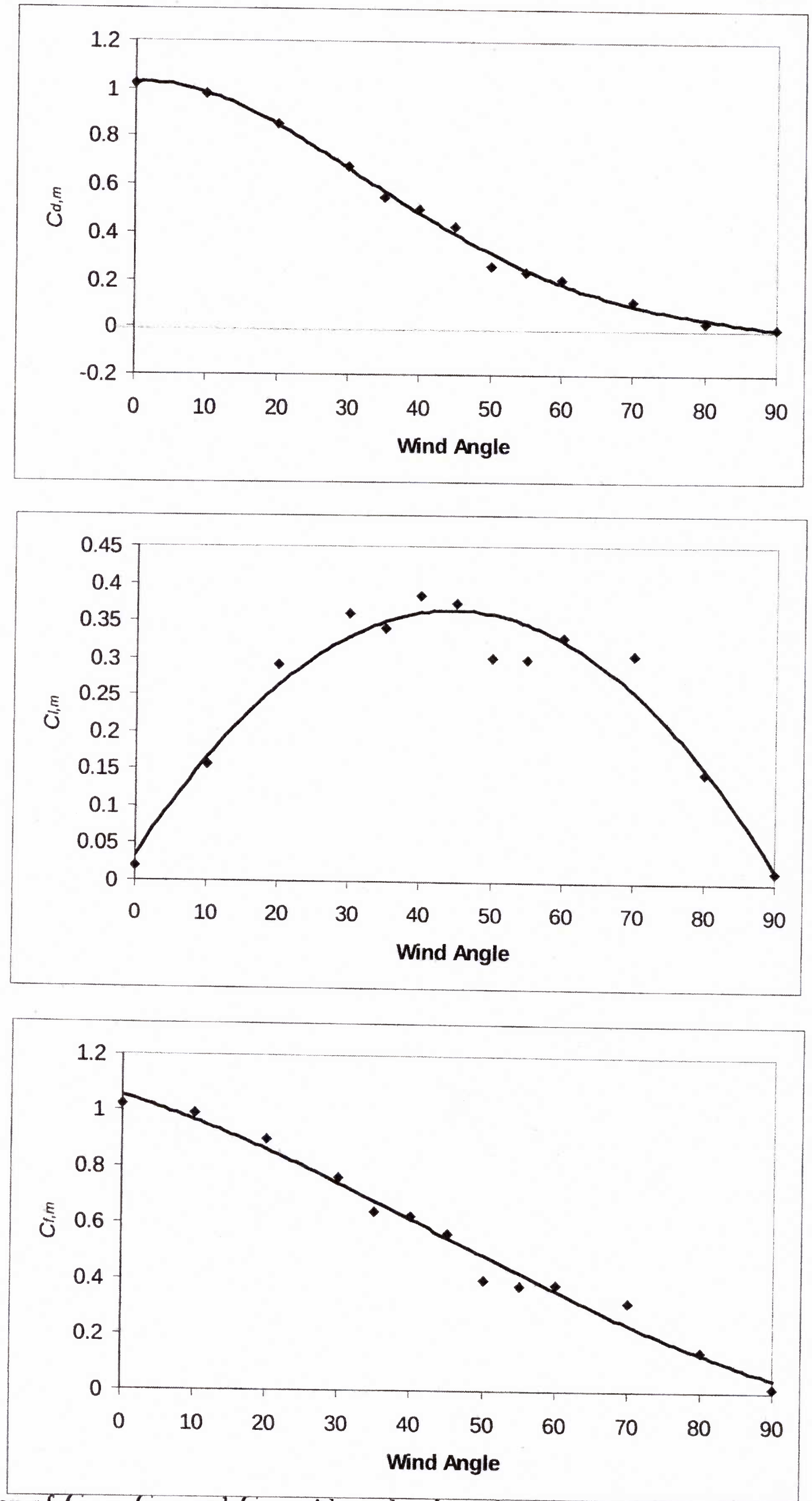


Fig. 6 Variation of $C_{d,m}$, $C_{l,m}$ and $C_{f,m}$ with angle of wind incidence for (β = 90°) for wire mesh

Fig.3: Variation of Cd (drag), Cl (lift) and resultant Cf with angle of incidence from the normal to the 6 x6 mm wire mesh, as measured by SERC (2008) in their wind tunnel at Chennai. Surprisingly SERC finds the low value of Cd = 1.0 at normal to the mesh!!

FIG4

11713
6827
18540

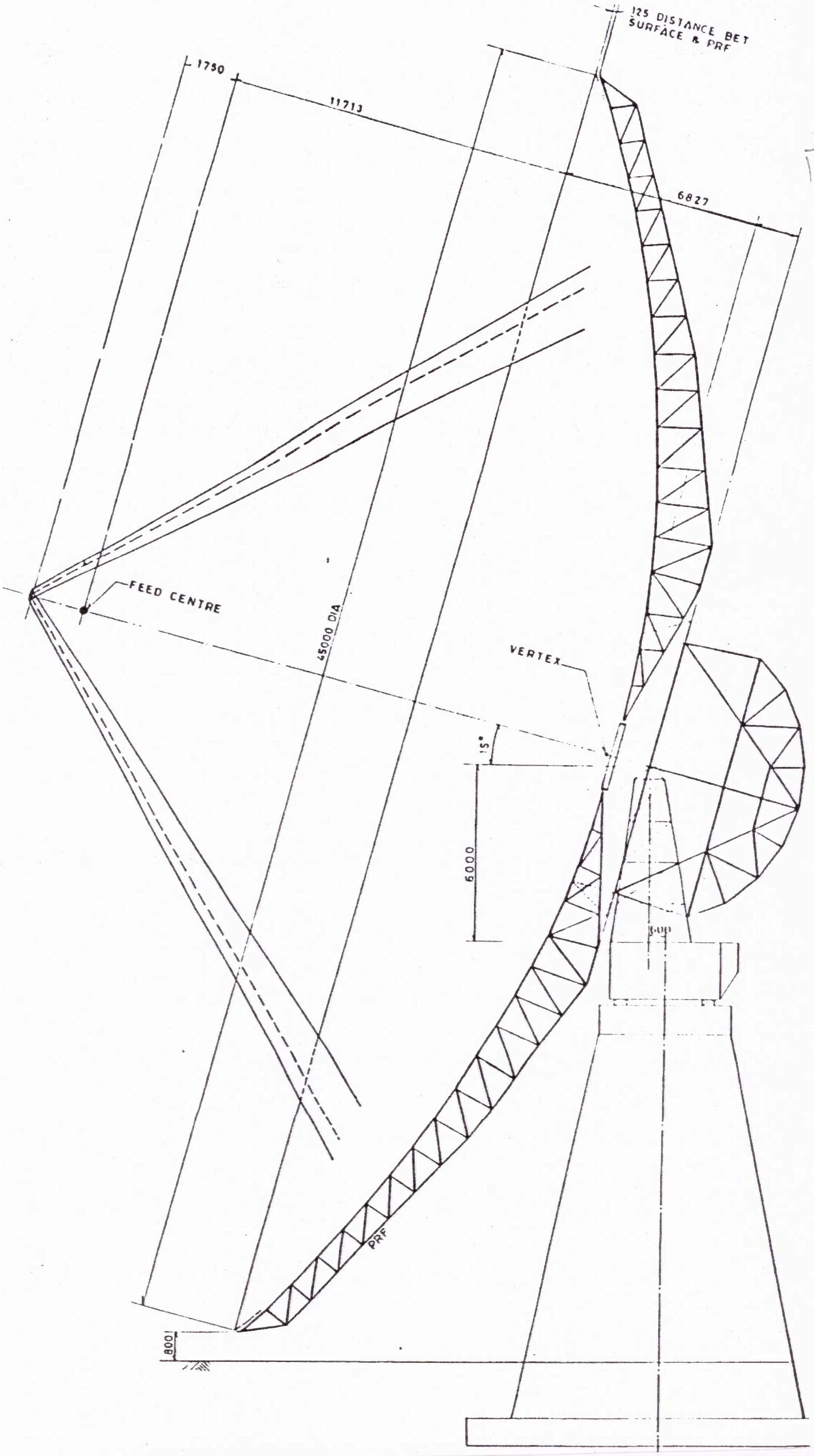


Fig. 4. Sectional elevation of the 45m parabolic dish (Swarup et al. 1991).

FIG. 5

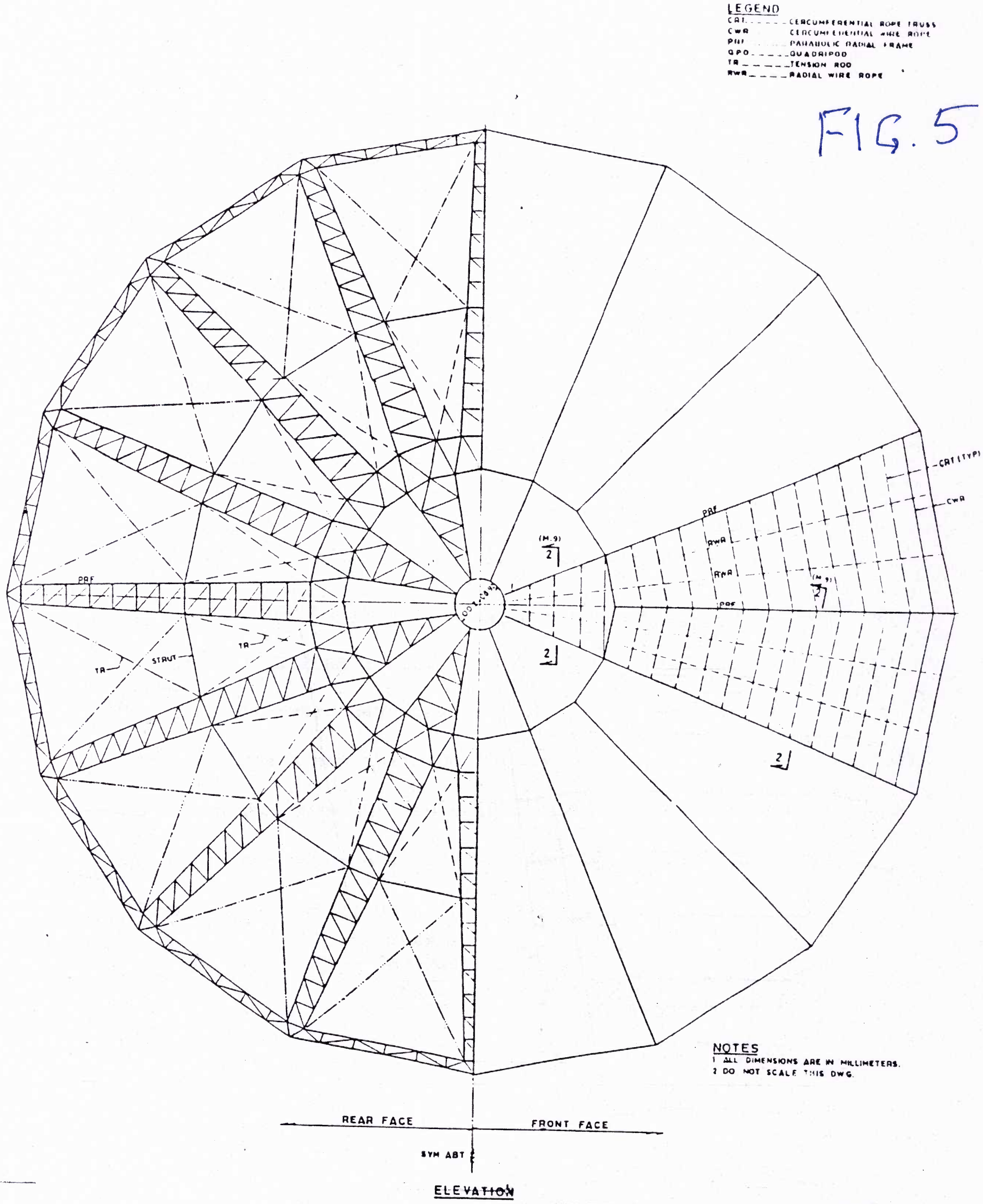


Fig. 5. Front and rear schematic of the 45m parabolic dish (Swarup et al. 1991).

FIG. 6

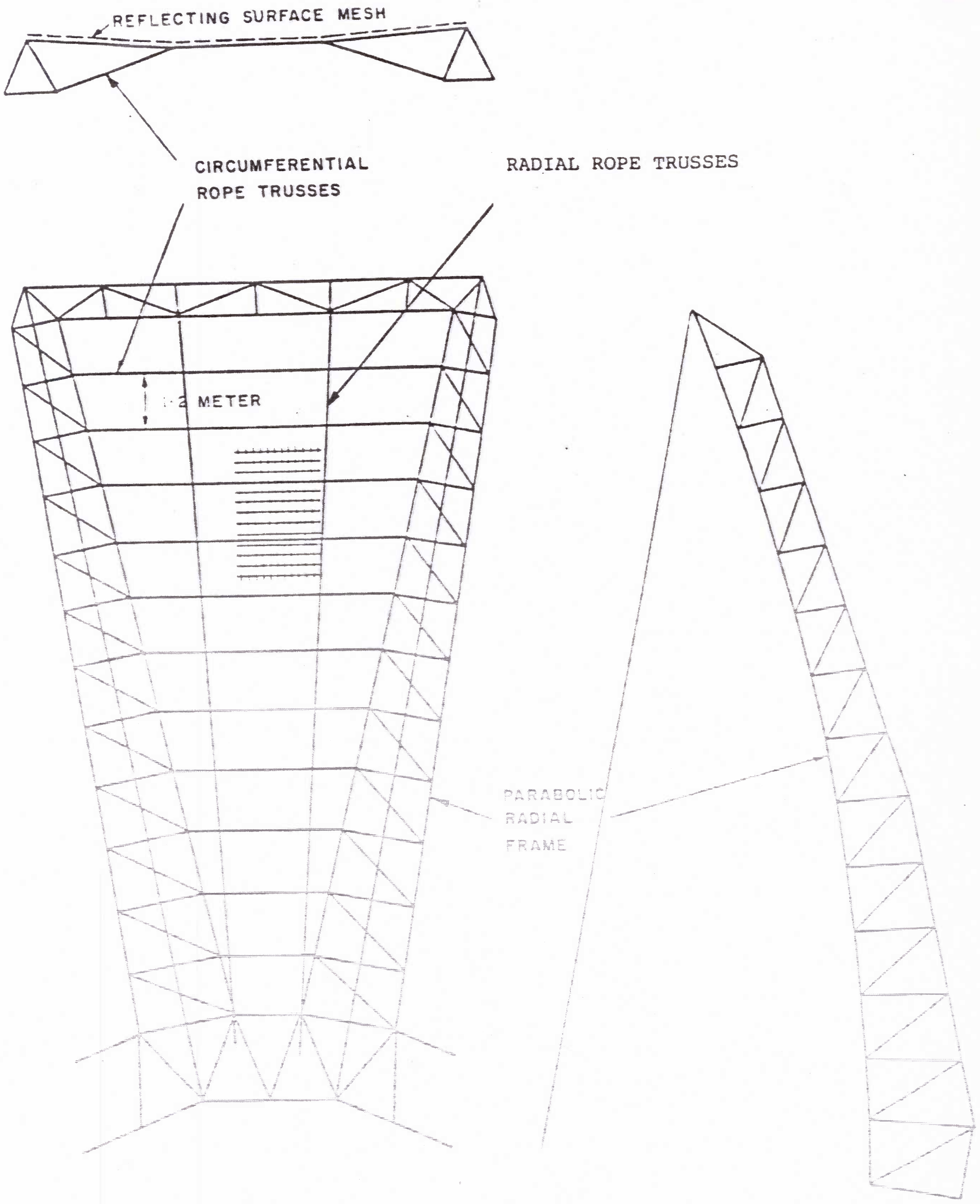


Fig. 6. A section of the dish, illustrating the SMART concept (Swarup et al. 1991).

A-1

Annexure A1: "Note to all concerned persons" with copies to senior persons at NCRA/GMRT giving the maximum values of the wind in each year from 1948 to 1990.

1/~~2~~4

Note to all concerned

Updated
28. 2

Dated : ~~7th~~ May 199~~3~~4.

Sub : **Statistics of high winds in the region including GMRT site.**
(1983-1990 data now included)

I enclose a table giving the record of maximum wind speed observed each year from 1948 to 1990 at the Pune Airport and/or IMD Station at Pune. In the last column we have converted the wind speed to a standard height of 10 m.

It may be noted that the highest wind observed has been 125.2 kmph at a height of 10 m on 11th May 1961, afternoon. From these data, one can derive the maximum wind likely to occur in a 50-year period, called the survival wind, to be 133 kmph for GMRT. From the data for the Ahmednagar and Pune Airports and for Pune IMD station, we have taken the Pune Airport data to be similar to actual conditions at the GMRT site. Data for several years at the Arvi Station has also validated our conclusions.

We have not been able to obtain from IMD the timings when these maximum winds occurred, except for six years, when the observed winds exceeded about 90 kmph, during the period 1958-64. Two conclusions can be arrived at from the table.

(a) The wind reached the highest value during the months of April, May or June in most of the years. But highest winds have also been recorded for a few years in the months of September, October and November (see histogram attached). Although July is generally a windy month, winds exceeding 80 kmph do not seem to occur during that month.

(b) Wind is generally high only from about noon to 8.00 p.m. Highest winds do not seem to have occurred at night time; but no guarantee can be given for the same from this limited statistics.

This data is only for information. However, we must take all steps for automatic stowlocking if mean wind over a period of half minute exceeds ~~40~~ 45 kmph.

14/2/94

G. Swarup

28/2/94

Encl. Table 1 & 2

Distribution

1. Shri S.C. Tapde/Shri B.S. Mathikari/Shri B.C. Joshi
2. Prof. V.K. Kapahi/Prof. S. Ananthakrishnan/Prof. A.P. Rao
3. All Engineers at Khodad
4. Notice Board, Khodad.

See Back side

GS:tsv:93.5.7.

A1/2-31

Table 1. **MAXIMUM WIND RECORDED AT PUNE AIRPORT DURING 1948-1990 YE**

Year	Date	Time	Actual Sensor height (m)	Maximum wind speed for actual height (km per hr)	Direction	Estimated Maximum wind (kmph) for 10 m ht. [$V(z) \alpha Z^{0.09}$]
1948	Nov 22	-	39.6	77	WW	>90 kmph ↓ 68.0 ↓ >
1949	Jun/July 1 / 14	-	"	69	WSW/NW	61.0
1950	Apr 26	-	"	93	NE	82.2
1951	Oct 22	-	"	77	E	68.0
1952	Oct 1	-	"	79	NE	69.8
1953	Apr / June 5 / 12	-	"	105	ESE/E	92.8
1955	May 7	-	7.5	105	E	107.8
1956	Apr 17	-	"	77	ENE	79.0
1957	May 25	-	"	79	ESE	81.1
1958	May 25	15.50	"	94	WSW	96.5
1959	Apr 27	19.10	"	102	SSE	104.7
1960	May 11	18.40	"	106	E	108.8
1961	May 11	15.20	"	122	E	125.2
1962	May 22	15.40	"	94	W	96.5
1963	June 15	-	"	76	W	78.0
1964	June 7	15.15	"	104	NW	106.7
1965	Apr 15	-	"	76	NE	78.0
1966	May 2	-	"	70	NE	71.8
1967	June 5	-	"	60	N	61.6
1968	Apr 25	-	"	70	N	71.8
1969	June 17	-	"	70	SW	71.8
1970	May 25	-	"	74	N	75.9
1971	May 29	-	"	80	N	82.1
1972	May 17	-	"	93	N	95.4
1973	May 20	-	"	80	N	82.1
1974	Sept. 14	-	"	108	NE	110.8
1975	May 28	-	"	74	N	75.9
1976	June 4	-	"	64	WSW	65.7
1977	Nov. 3/Sep 29/July 5	-	"	60	W/WSW/N	61.6
1978	April 26	-	"	93	SW	95.4
1979	May 30	-	"	75	WSW	77.0
1980	May 3	-	"	63	S	64.7
1981	May 1	-	"	72	NW	73.9
1982	July 18	-	"	66	WSW	67.7
1983	June 1	-	-	89	N	91.4
1984	Sept. 23	-	-	72	WNW	73.9
1985	May 18	-	-	90	NE	92.4
1986	Dec 27	-	-	81	E	83.1
1987	May 20	-	-	76	ESE	78.0
1988	June 8	-	-	74	NNE	75.9
1989	Jan 26	-	-	64	WNW	65.7
1990	July 4	-	-	56	W	57.5

U2

GS:tsv:94.2.28.

G. Swarup

1.026

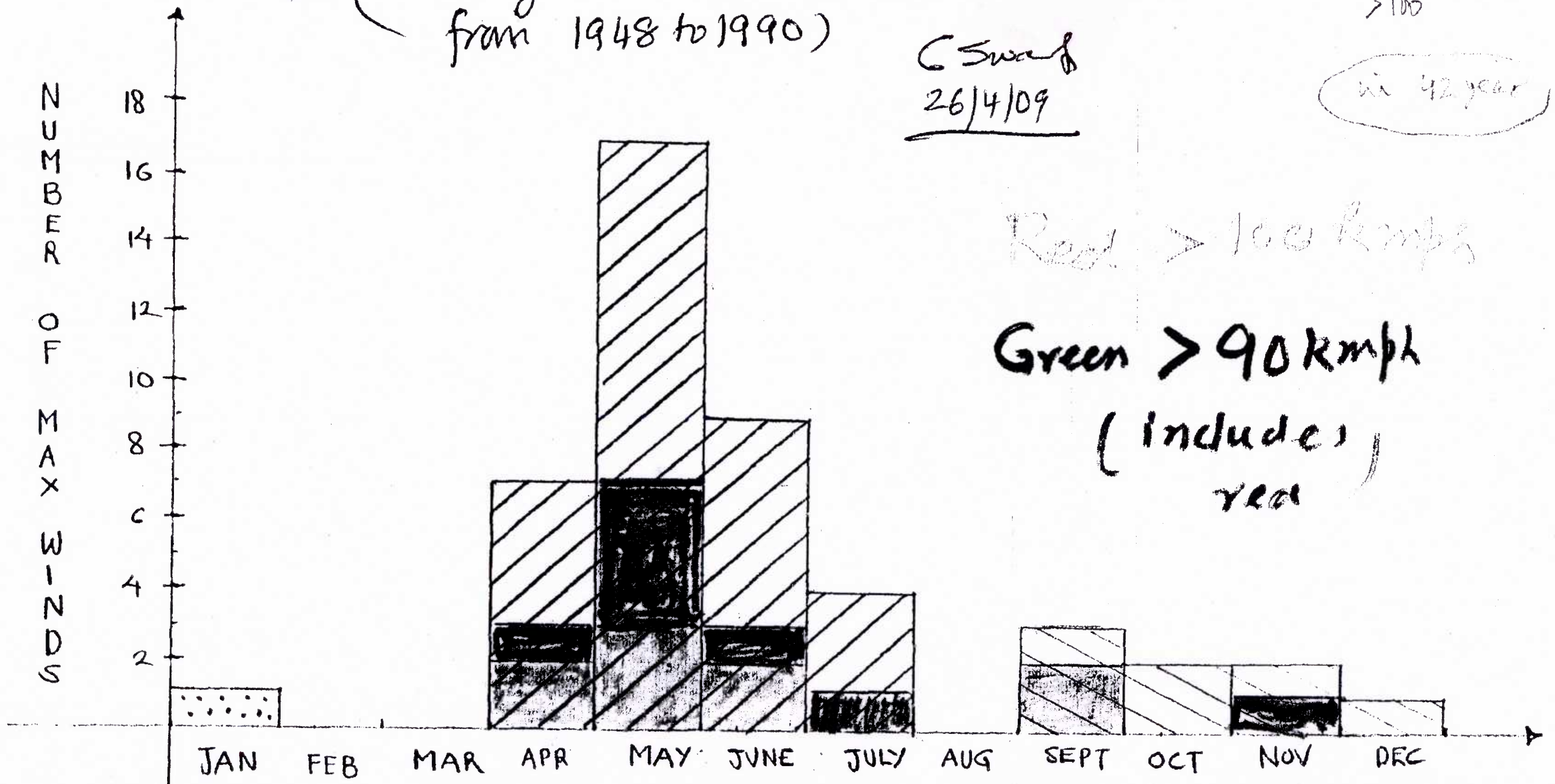
A1-3/A
3/3

Dec = 2
Sept = 2
Jan
Nov
9 >100
12 >90
in 42 year

OCCURANCE OF MAXIMUM WIND

& (each year maximum
from 1948 to 1990)

C Swarf
26/4/09



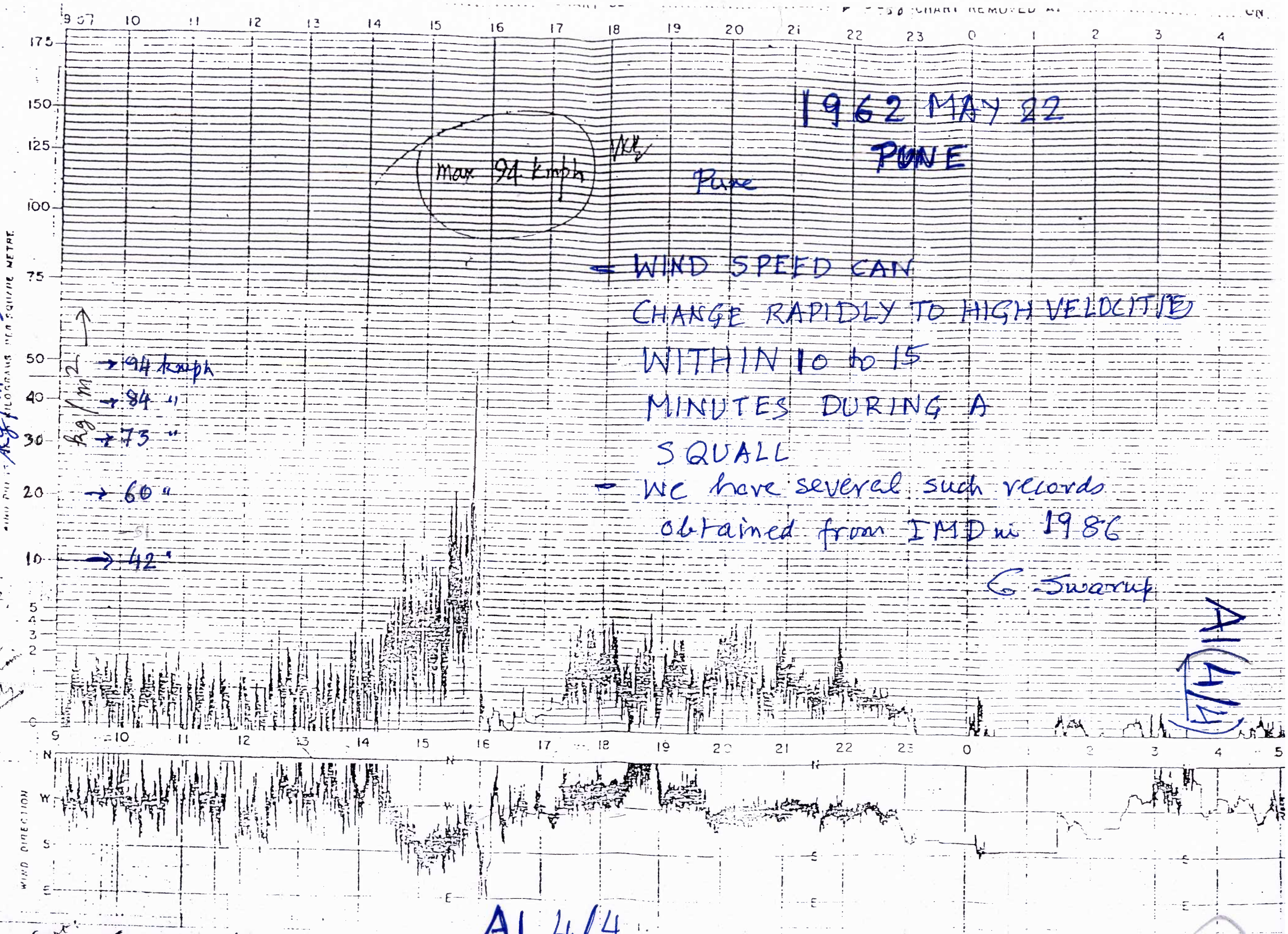
Red > 100 kmph

Green > 90 kmph
(includes red)

YEAR OF MONTH SIMLA office +
(DATA FROM 1948 – 1990 AT PUNE AIRPORT)

BCJ/28/2/94

1962 MAY 22
PUNE



← WIND SPEED CAN CHANGE RAPIDLY TO HIGH VELOCITIES WITHIN 10 to 15 MINUTES DURING A SQUALL

– We have several such records obtained from IMD in 1986

G. Swarup

AI (4/4)

AI 4/4

Mean speed given only if lasted for atleast 3 Minutes (3 Min average) It generally varies [illegible] a [illegible] in [illegible] speed only

Old Eqpt: Dynes PT Anemometer (Pressure Tube) Recording

Present Eqpt: ~~DWRE~~ DRWE Distant Reading Wind Eqpt.

Annexure A2: Calculated Risk for the assumed maximum wind (survival) for a return period of T years (see Table 2.5 of Sachs (1978)) reproduced below.

A2

J

(iii) *Calculated risk*

Page 41

The maximum velocity V_{max} for a return period of T years is obviously itself a statistical average, based on the average value of several T-year periods. It has been calculated[(25)] that V_{max} has a 63% probability of being reached in T years, so that a structure, if designed to velocity V_{max}, has a 63% chance of failure.

There is a percentage risk in selecting any design wind speed, but this decreases with increasing return period T. Table 2.5 gives design return periods for calculated risks for various structural lifetimes. Taking the example of a 20-year structural life, a 10% chance of destruction requires a design to a 190-year return period. Translating this into wind speeds at Cardington (Fig. 2.28), for

$$T = \underline{20} \text{ years}, \quad V_{max} = 93 \text{ m.p.h.}, \leftarrow$$

$$T = \underline{190} \text{ years}, \quad V_{max} = \underline{115} \text{ m.p.h.} \leftarrow$$

TABLE 2.5. RETURN PERIOD (YEARS) REQUIRED FOR VARIOUS DESIGN LIFETIMES AT CERTAIN RISKS(25)

Desired life (yr.)	Calculated risk								
	0·632	0·500	0·400	0·333	0·300	0·250	0·200	0·100	0·050
2	3	3	4	5	6	7	9	20	40
10	11	15	20	25	29	25	45	95	196
— 20	20	29	39	49	56	69	90	190	390
50	50	72	98	124	140	173	224	475	975
100	100	144	196	247	280	345	448	949	1950

The increase in design wind speed, from 93–115 m.p.h., is within the usual safety factor. As an alternative, the designer may construct his structure to a particular wind speed, say 150 m.p.h., and quote the calculated risks for a particular structural lifetime. In the case of Cardington, the risk is negligibly small.

SACHS : WIND FORCES IN ENGINEERING
Pergamon, 1978

(iv) *National data*

Annexure A3: Basic wind data recommended for Pune by Lashmanan et al. (2009). CURRENT SCIENCE, Vol. 96, pp. 911–922 (2009)

A3

LAKSHMANAN et al.

(T)

Table 2. Design basic wind speed (m/s)/wind zone for various IMD meteorological stations (with all annual maximum wind speeds or values over threshold)

			Prediction with Gumbel using all annual peak values			Prediction with Gumbel using annual peak values over the threshold		
Station ID	Wind zone IS:875	Basic wind speed IS:875 V_b (m/s)	V_{bR} (m/s)	Wind speed with $T = 50$ yrs	Percentage difference IS:875	V_{bR} (m/s)	Wind speed with $T = 50$ yrs	Percentage difference IS:875
AHMEDABAD	2	39	42	36	8	43	37	10
AMRITSAR	4	47	54	47	16	56	48	19
BAGHOGRA(A)	4	47	42	36	–11	42	36	–11
BANGALORE	1	33	30	26	–9	34	29	–4
BARODA	3	44	41	36	–6	42	37	–4
BHOPAL BAIRAGARH	2	39	49	42	26	45	39	16
BIDAR (A)	2	39	51	44	30	52	45	33
BOMBAY	3	44	32	28	–27	33	28	–26
BOMBAY/SANTACRUZ	3	44	39	34	–11	40	35	–8
CALCUTTA	5	50	46	40	–7	48	41	–5
CALCUTTA/DUM DUM	5	50	52	45	4	54	46	7
CHABUA (A)	5	50	–	–	–	–	–	–
COCHIN (N.A.S)	2	39	43	37	10	44	38	14
GAYA	2	39	39	33	–1	56	48	44
GOPALPUR	2	39	46	39	17	47	40	20
HAKIMPET (A)	3	44	59	51	33	–	–	–
HASHIMARA (A)	4	47	48	41	2	50	43	6
HYDERABAD (A)	3	44	40	34	–10	41	35	–8
INDORE	2	39	47	40	20	42	36	7
JAGDALPUR	2	39	44	38	14	46	39	17
JAIPUR/SANGANER	4	47	45	39	–4	46	40	–2
JAMNAGAR (A)	5	50	46	40	–8	40	35	–19
KALAIKUNDA (A)	5	50	58	50	17	55	47	9
KODAIKANAL	2	39	41	36	6	41	35	4
LUCKNOW/AMAUSI	4	47	54	47	15	55	48	17
MADRAS/MINAMBAKKAM	5	50	39	34	–21	45	39	–10
MADRAS HARBOUR	5	50	46	40	–8	53	45	5
MANGALORE H.P./PANAMBUR	2	39	40	35	3	38	33	–3
MORMUGAO	2	39	40	35	4	42	36	7
NAGPUR/SONEGAON	3	44	43	37	–2	49	43	12
MANGALORE (A)	1	33	34	29	2	36	31	10
NEW DELHI/SAFDJNG	4	47	45	39	–3	47	40	0
NEW KANDLA	5	50	45	39	–10	46	40	–8
OZAR 2	39	52	45	33	–	–	–	
PALAM (A)	4	47	53	45	12	54	47	15
PORT BLAIR	3	44	47	40	6	48	41	9
PUNE ~~2~~ → shift by one column!	2 ~~39~~	39 ~~36~~	36 ~~31~~	31 ~~–9~~	–9 ~~42~~	42 ~~36~~	36 ~~6~~	6
PUNE (A) LOHAGAON	2	39	48	$\boxed{41}$	22	50	43	28
RAIPUR	2	39	43	37	10	45	39	16
SAGAR ISLAND	5	50	52	45	3	53	46	6
TAMBARAM (A)	5	50	45	39	–10	–	–	–
TIRUCHIRAPALLI (A)	4	47	48	41	2	49	42	3
TRIVANDRUM (A)	2	39	33	28	–16	34	29	–14
TRIVANDRUM/TIRUVN	2	39	29	25	–25	30	26	–22
TUTICORIN	2	39	36	31	–6	38	32	–4
TUTICORIN H.P.	2	39	39	34	0	41	35	5
VERAVAL	5	50	43	37	–14	45	38	–11
VISHAKHAPATNAM (A)	5	50	49	42	–3	50	43	0
VIZG RSRW	5	50	49	43	–1	51	44	3

PUNE →

have variations of around 10% may be ignored while considering a wind speed revision either to higher or to a lower wind zone. Figure 11 shows schematically the details given in Table 2, with red circles indicating a revision upward and blue circles demanding no revision of the current wind zone.

Cat.

only 10%

1.05 → 0.91

J

A4

Annexure A4: Cd values for various sizes of mesh of low solidity reproduced from the paper by Swarup (2007), with some additional data added.

[PAGE FROM SWARUP (2007), "WIND ENGINEERING ..." NCWE-2007]

Table 1. Comparison of calculated values of C_d using Eqns 5 and 6 of this paper with measured values for various values of solidity and porosity for wire meshes made of round wires. * Calculated by GS using EQ. given by MUROTA, 1976

** RECENT MEASUREMENT BY SERC, Chennai, 2008 for NCRA/TIFR

Sr. No.	Mesh size (mm)	Porosity (β)	Solidity (S)	k (Eqn.5)	C_d calculated (k/S)	C_d Measured	Reference	MUROTA 1976 *
1.	20×20×0.55	0.973	0.028	0.028	1.00	0.98	NAL(1987)	1.03
2.	15×15×0.55	0.928	0.072	0.080	1.11	1.07	NAL(1987)	1.08
3.	12×12×0.55	0.910	0.090	0.103	1.15	1.23	NAL(1987)	1.09
4.	10×10×0.55	0.893	0.107	0.126	1.17	-		1.12
5.	6×6×0.55	0.825	0.175	0.231	1.32	1.33		1.17
6.	15×15×1.4	0.822	0.178	0.237	1.33	1.46	Koppen(1987)	1.26
7.	7.87×7.87×1.12	0.736	0.264	0.410	1.55	1.50	Wyatt(1964)	1.30
8.	-	-	-	-	-	1.30	Cohen et al. (1964)	
** 9	6×6×0.55	0.825	0.175	0.231	1.32	1.00	SERC-2008	

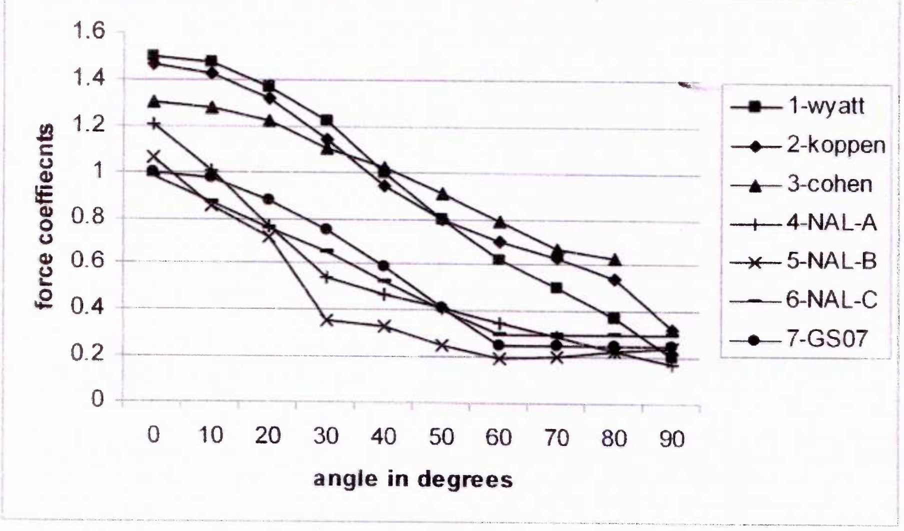


Fig.1 Curves 1 and 2 give measured values of force coefficients C_d for wire meshes of sizes 7.87mm×7.87mm×1.12mm, 15mm×15mm×1.4mm respectively. Curve 3 refers to Cohen et al. Curves 4 to 6 give values for 12mm×12mm×0.55mm,

Annexure A5 A brief comparison of the stress ratio values in the computer outputs of DISHCRAD (in blue) and RIGIDISH (red) by TCE, for some typical cases with relatively high stress factors (made by the Author). It is seen that the stresses are lower for the RIGIDISH case by 5 to 15%. For bracings and struts stress ratio are more than 30% lower for RIGIDISH.

J A5

pp. 138 -153 for DishCrad

BRACINGS & STRUTS NOT STUDIED By GS

23/05/09

Sr / LINE No.	ITEM	SIZE mm/mm	l cm	MEMB NO	COMB *	LOC	STRESS RATIOS 2 AXIAL STAT	4 STUD BEND STAT	5 CURV BEND	6 WLDL BEND STAT	7 TOTAL STAT	I
1A	QUAD TOP FRAME, BOT. LAG	76.1/4.5	33	176	4	CC	0.69				0.87	WL Dish Sky
		76.1/4.5	33	219	4	CC	0.58				0.72	QUAD
1B	As above for RIGIDISH	76.1/4.5	33	177	3	CE	1.03			0.58 ~~0.58~~	1.03	Dead LOAD Dish Horizon PRF-1
			45.6	220	3	CE	0.84				0.84	
222 1A	PRF I TOP No. (14)	~~222~~ 88.9/4.85	124.2	4257	29	CC	0.53	0.02	0.10		0.75	
1B		"		4257			0.54	0.01	0.10		0.65	
235 1A	PRF II TOP No. (13)	101.6/4.85	124.2	1522	25	CC	0.45	0.02	0.07		0.64	
1B		"		1522	25	CC	0.46	0.01	0.07		0.54	PRF-2
236	PRF 2 TOP No. (14) ←	101.6/4.85	124.2	4259 4258	29	CC	0.52	0.02	0.08		0.73	
	No. 14	"		4256	34	CC	0.55	0.01	0.09		0.64	
~~1383~~ 244	PRF III TOP No. (4)	76.1/4.5	123.9	1383	3	CC	0.53	0.07	0.11		0.82	
244		"		13 83	3	CC	0.66	0.04	0.13		0.77	
245	PRF III Top	76.1/4.5	124.0	1399	3	CC	0.53	0.07	0.11		0.81	
245	No (5)	"		1399	3	CC	0.55	0.04	0.11		0.70	PRF-3
246	PRF-3-Top	76.1/4.5	124.1	1415	3	CC	0.49	0.06	0.11		0.79	
246	No (6)	"		1415	3	CC	0.54	0.04	0.11		0.69	
253	PRF 3-Top	101.6/4.85	124.2	1519	34	CC	0.49	0.02	0.08		0.69	
253	No. (13)	"		1519	34	CC	0.51	0.01	0.08		0.66	
254	PRF-TOP	101.6/4.85	124.2	4255	34	CC	0.53	0.62	0.69		0.74	
	No. (14)	"	"	4259	29	CC	0.62	0.01	0.10		0.72	
464	RIM: Top Outr	60.3/4.5	147.7	3152	33	CC	0.44	0.02	0.02		0.59	
	"	"	"	"	33	"	0.46	Board .02			0.48	
473	RIM: Top Innr	60.3/4.5	140.7	3209	13	CC	0.58	0.02	0.02		0.78	
	"	"	"	"	13	"	0.59	0.02			0.62	
483	RIM: Top Innr	60.3/4.5	140.7	3286	4	CC	0.57	0.02	0.02		0.56	RIM
	"	"	"	"	4	CC	0.41	0.01			0.43	
495	RIM BOT Innr	88.9/4.85	143.7	3295	33	CC	0.60	0.02	0.02		0.76	
	"	"	"	"			0.63	0	0		0.63	
~~458~~ 702	HUB BOT Innr	193.7/5.9	126.6	3994	2	CC	0.63				0.78	
	"	"	"	"	"	"	0.89				0.89	
709	HUB BOT Innr	193.7/5.9	126.6	3966	1	CC	0.62				0.78	
	"	"	"	"	"	"	0.89				0.89	HUB
727	HUB TOP	219.1/5.9	84.9	3987	33	CC	0.71				0.88	
	"	"	"	"	"		0.87				0.87	
816	HUB FACE VERT BRCG	127.0/5.4	199	4175	3	CC	0.57		.01		0.87	
	"	"	"	"	"		0.77				0.78	

Clarified - [illegible]
Clarified

* COMB 33 DISH TO 75° from ZENITH

COMB, 2,3,4 Wind Loads Dish to Sky : Wind front/side
ZENITH

Annexure A6: R.M.S. Surface Errors in mm with respect to the best fit paraboloid of the 45m dishes for 6 positions from horizon to zenith. Displacement of the focus is less than 5 mm in x, y and z direction. (details in document C7).

A6

NOT INCLUDING DEFLECTION OF THE QUADRIPOD

TCE.G18/DR/CAL/153-RMSERR	TATA CONSULTING ENGINEERS	SECTION R&D & CIVIL
	G M R T	SH 5 OF

TABLE - 2 : RMS SURFACE ERRORS IN MILLIMETERS WITH RESPECT TO BFP (mm)

Sl no	Dish position form horizon	Wind direction	RMS surface errors case-A	case-B	case-C	Remarks
1	110°	FW	2.84	2.84	2.91	See footnote
		RW	-	2.85	2.96	
		SW	-	2.85	2.94	
2	90°	FW	3.06	3.03	3.38	
		RW	-	3.10	2.96	
		SW	-	3.06	3.15	
3	75°	FW	3.04	3.00	2.94	
		RW	-	3.07	3.35	
		SW	-	3.04	3.12	
4	60°	FW	3.45	3.40	3.21	
		RW	-	3.50	3.86	
		SW	-	3.45	3.52	
5	45°	FW	3.91	3.87	3.66	
		RW	-	3.97	4.30	
		SW	-	3.91	3.98	
6	30°	FW	4.32	4.28	4.13	
		RW	-	4.35	4.60	
		SW	-	4.32	4.36	
7	15°	FW	4.57	4.56	4.49	
		RW	-	4.59	4.73	
		SW	-	4.57	4.62	

Note :

⇒
Case-A : DL only (0 m/sec wind speed)
Case-B : DL+WL (5.5 m/sec wind speed) = 20kmph
Case-C : DL+WL (13.9 m/sec wind speed) = 50.00 kmph
FW : Front wind
RW : Rear wind
SW : Side wind

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DATE :	DATE :				

Annexure A7 (4 pages): gives few results from the computer analysis of YOKE (document C4), regarding forces and moments at the elevation and azimuth bearings.

A7

1/4

TCE-G18-DR-CAL-153 -YOKE	TATA CONSULTING ENGINEERS	SECTION R&D & CIVIL
	G M R T	SH 9 OF

TABLE - 1 : Forces acting on yoke structure at elevation bearing and elevation pinion points

Sl no	Load cases		Elevation bearing points						Pinion point		
	Dish position	Load case	Joint 1			Joint 802			Joint 391		
			Fx (t)	Fy (t)	Fz (t)	Fx (t)	Fy (t)	Fz (t)	Fx (t)	Fy (t)	Fz (t)
1	all dish posns.	DL	0.4	-	-46.0	-	-	-46.8	-0.9	-	-
2	dish @ -20 deg	WL-front	38.3	-	-2.5	38.6	-	-2.5	-39.2	-	3.4
		WL-side	6.7	35.0	-19.5	-6.7	-	19.5	-	-	-
3	dish facing sky	WL-front	-36.1	-	-1.7	-36.1	-	-1.7	37.2	-	3.3
		WL-side	-	35.0	-20.6	-	-	20.6	-	-	-
4	dish @ 15 deg	WL-front	-38.0	-	-2.5	-37.8	-	-2.5	38.8	-	3.4
		WL-side	-5.3	35.0	-19.9	5.3	-	19.9	-	-	-
5	dish @ 30 deg	WL-front	-39.9	-	-3.2	-39.6	-	-3.2	39.4	-	3.4
		WL-side	-9.3	34.8	-18.3	9.4	-	18.33	-	-	-
6	dish @ 45 deg	WL-front	-39.7	-	-3.4	-39.4	-	-3.4	35.8	-	3.1
		WL-side	-13.3	34.5	-15.6	13.3	-	15.6	-	-	-
7	dish @ 60 deg	WL-front	-37.5	-	-2.9	-37.3	-	-2.9	28.7	-	2.5
		WL-side	-15.9	34.0	-11.7	15.9	-	11.7	-	-	-
8	dish @ 75 deg	WL-front	-34.0	-	-1.68	-33.2	-	-1.7	19.7	-	1.7
		WL-side	-18.0	33.8	-7.52	18.4	-	7.5	-	-	-

Note :

y axis is parallel to the elevation axis

z axis is vertical (gravity) axis & coincides with the axis of the azimuth bearing

x axis is perpendicular to the y and z axes

Design wind speed at 10 m height above GL : 37 m/sec

Fx, Fy and Fz are forces along x, y and z axes

DL = Dead load

WL-front = Wind load for wind in direction perpendicular to elev. axis

WL-side = Wind load for wind along elevation axis

Dish position is measured w.r.t " dish facing sky" (zenith) position

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TABLE - 2 : Forces and moments at centre of azimuth bearing

Sl no	Dish position	Load case	Force along x-dir (t)	Force along y-dir (t)	Force along z-dir (t)	Moment about x-axis (t.m)	Moment about y-axis (t.m)	Moment about z-axis (t.m)
1		DL of yoke	-	-	28.3	0.5	-4.8	-
2		DL (dish+ cradle)	-	-	99.1	-	-56.5	-
3	dish @ -20 deg	WL (front)	-43.3	-	2.0	-	-539.5	-1.1
		WL (side)	-	-40.0	-	508.0	-	39.7
4	dish facing sky	WL (front)	40.0	-	0.2	-	492.6	-
		WL (side)	-	-40.0	-	518.0	-	-22.4
5	dish @ 15 deg	WL (front)	42.0	-	1.8	-	516.0	-
		WL (side)	-	-40.0	-	511.9	-	-70.6
6	dish @ 30 deg	WL (front)	45.1	-	3.1	-	546.0	-
		WL (side)	-	-39.5	-	495.0	-	-107.7
7	dish @ 45 deg	WL (front)	48.3	-	3.8	-	556.0	1.2
		WL (side)	-	39.5	-	468.0	-	-143.0
8	dish @ 60 deg	WL (front)	51.7	-	3.4	-	544.0	-
		WL (side)	-	-39.0	-	427.0	-	-167.0
9	dish @ 75 deg	WL (front)	53.2	-	1.80	-	520.0	-
		WL (side)	-	-38.7	-	386.0	-	-186.0

Note :

y axis is parallel to ~~the elevation~~ axis

z axis is vertical (gravity) axis & coincides with the axis of the azimuth bearing

x axis is perpendicular to the y and z axes

Design wind speed at 10 m height above GL : 37 m/sec

Fx, Fy and Fz are forces along x, y and z axes

DL = Dead load

WL-front = Wind load for wind in direction perpendicular to elev. axis

WL-side = Wind load for wind along elevation axis

Dish position is measured w.r.t " dish facing sky" (zenith) position

GS 25/2/93

Y into paper or out?

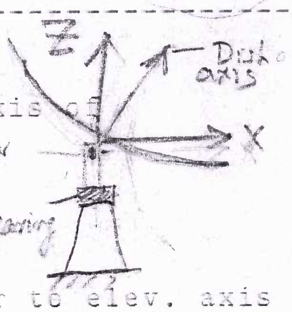

TABLE - 3 : Mass and mass moments of inertia - dish facing sky & horizon

Sl no	Description	Units	Dish + Cradle at elevation bearing level	Dish + Cradle + Yoke at azimuth bearing level
	DISH FACING SKY			
1	M : mass	Kg sec^2/cm	92.65	121.08
2	Mxx : mass moment of inertia	Kg.sec^2.cm	0.729e8	1.460e8
3	Myy : mass moment of inertia	Kg.sec^2.cm	0.733e8	1.436e8
4	Mzz : mass moment of inertia	kg.sec^2.cm	0.872e8	0.908e8 ← Use
	DISH FACING HORIZON			
1	M : mass	Kg sec^2/cm	92.65	121.08
2	Mxx : mass moment of inertia	Kg.sec^2.cm	0.872e8	1.603e8
3	Myy : mass moment of inertia	Kg.sec^2.cm	0.733e8	1.436e8
4	Mzz : mass moment of inertia	kg.sec^2.cm	0.729e8	0.765e8

TABLE - 4 : Deflections in mm for yoke structure

Load case	Joint no 1 (EL AXIS)			Joint no 802 (EL AXIS)			Joint no 391 (PINION POINT)		
	x	y	z	x	y	z	x	y	z
Fx=1000	.2090	-.0026	-.0094	.1848	-.0006	-.0094	.0278	.0014	-.0030
Fy=1000	-.0534	.4842	-.0056	.0482	.0759	.0285	-.0006	.0248	.0004
Fz=1000	-.0090	.0114	.0221	-.0098	-.0115	.0221	-.0016	-.0002	.0004
Mx=1000	.0016	.0037	-.0076	-.0016	.0037	.0076	.0000	.0025	-.0000
My=1000	.0343	-.0004	-.0016	.0339	.0003	-.0016	-.0114	.0037	.0053
Mz=1000	.1001	-.0111	-.0015	-.0948	-.0107	.0017	.0340	.0003	.0016

Note :
Fx , Fy & Fz are forces in kg. along x , y & z axes respectively .
Mx , My & Mz are moments in kg. m. about x , y & z axes respectively .

7-4

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TCE-G18-DR-CAL-153 -YOKE	TATA CONSULTING ENGINEERS	SECTION R&D & CIVIL
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TABLE - 5 : Stiffnesses of yoke structure

Sl no	Stiffness	Direction	Stiffness value	Units
1	Kxx	along x-axis	47846	kg/cm
2	Kyy	along y-axis	20661	kg/cm
3	Kzz	along z-axis	451263	kg/cm
4	Kθx	about x-axis	1.478e11	kg.cm/rad
5	Kθy	about y-axis	1.122e10	kg.cm/rad
6	Kθz	about z-axis	8.485e09 ←	kg.cm/rad

TABLE - 6 : Natural frequencies - dish facing sky & horizon

Sl no	Direction	Stiffness K	Mass or mass moment of inertia M	Natural frequency $w=(K/M)^{0.5}$ rad /sec	 w/2.π cycles/sec
	DISH FACING SKY				
1	Along x-axis	47846	121.08	19.80	3.16
2	Along y-axis	20661	121.08	13.06	2.08
3	Along z-axis	451263	121.08	61.05	9.72
4	About x-axis	1.478e11	1.460e8	31.82	5.06
5	About y-axis	1.122e10	1.436e8	8.84	1.41 → 1.69 Hz
6	About z-axis	8.485e09	0.908e8	9.67	1.54 ✓ GS Az U
	DISH FACING HORIZON				
7	Along x-axis	47846	121.08	19.88	3.16
8	Along y-axis	20661	121.08	13.06	2.08
9	Along z-axis	451263	121.08	61.05	9.72
10	About x-axis	1.478e11	1.603e8	30.36	4.83
11	About y-axis	1.122e10	1.436e8	8.38	1.41
12	About z-axis	8.485e09	0.765e8	10.53	1.68 ✓ CS (Az U

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DATE		DATE			

See caption below A8 (1/2)

TABLE - 1 : Masses and mass moments of inertia - dish facing sky & horizon

Sl no	Description	Units	Dish + Cradle at elevation bearing level	Dish + Cradle + Yoke at azimuth bearing level
	DISH FACING SKY			
1	M : mass	$Kg.sec^2/cm$	92.65	121.08
2	Mxx : mass moment of inertia	$Kg.sec.cm^2$	0.729e8	1.460e8
3	Myy : mass moment of inertia	$Kg.sec.cm^2$	0.733e8	1.436e8
4	Mzz : mass moment of inertia	$Kg.sec^2.cm$	0.872e8	0.908e8
	DISH FACING HORIZON			
1	M : mass	$Kg.sec^2/cm$	92.65	121.08
2	Mxx : mass moment of inertia	$Kg.sec.cm^2$	0.872e8	1.603e8
3	Myy : mass moment of inertia	$Kg.sec.cm^2$	0.733e8	1.436e8
4	Mzz : mass moment of inertia	$Kg.sec^2.cm$	0.729e8	0.765e8

TABLE - 2 : Deflection in mm for yoke structure

Load case	Joint 1			Joint 802			Joint 391		
	Dx	Dy	Dz	Dx	Dy	Dz	Dx	Dy	Dz
Fx=1000	.1567	-.0005	-.0073	.1554	.0003	-.0074	.0077	-.0001	.0005
Fy=1000	-.0011	.4359	-.0853	.0001	.0308	.0128	.0008	.0000	.0008
Fz=1000	-.0074	.0116	.0201	-.0074	-.0116	.0201	-.0007	-.0002	.0000
Mx=1000	.0152	.0003	-.0055	-.0015	.0003	.0055	.0000	.0010	-.0000
My=1000	.0300	-.0003	-.0013	.0299	.0002	-.0014	-.0116	-.0031	.0047
Mz=1000	.0337	-.0001	-.0015	-.0334	-.0001	.0015	.0001	.0003	.0000

Note :
Fx , Fy & Fz are forces in kg, along x, y & axes respectively
Mx , My & My are moments in kg m about x, y & z axes respectively

Annexure A8 (2 pages): gives few results from the computer analysis of YOKE-Stiffness (document C5), regarding Masses, Moments of Inertia, deflections of Yoke Structure (mm),stiffness and natural frequencies of the Yoke.

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A8-1

A8(2/2)

TABLE - 3 : Stiffness of yoke structure

Stiffness	Direction	Stiffness value	Units
Kxx	Along X - axis	63816	Kg cm
Kyy	Along Y - axis	22941	Kg cm
Kzz	Along Z - axis	496278	kg cm
Kθx	About X - axis	3.3969E11	kg.cm/rad
Kθy	About Y - axis	1.3317E10	kg.cm/rad
Kθz	About Z - axis	1.3827E10	kg.cm/rad

TABLE - 4 : Natural frequencies - dish facing sky & horizon

Sl no	Direction	Stiffness K	Mass or mass moment of Inertia M	Natural frequency	
				w=(K/M)$^{0.5}$ rad / sec	w/2. cycles/sec
	DISH FACING SKY				
1	Along X - axis	63816	121.08	22.96	3.65
2	Along Y - axis	22941	121.08	13.76	2.19
3	Along Z - axis	496278	121.08	64.02	10.19
4	About X - axis	3.3969E11	1.460E8	48.23	7.68
5	About Y - axis	1.3317E10	1.436E8	9.63	1.53
6	About Z - axis	1.3827E10	0.908E8	12.34	1.96
	DISH FACING HORIZON				
1	Along X - axis	63816	121.08	22.96	3.65
2	Along Y - axis	22941	121.08	13.76	2.19
3	Along Z - axis	496278	121.08	64.02	10.19
4	About X - axis	3.3969E11	1.603E8	46.03	7.33
5	About Y - axis	1.3317E10	1.436E8	9.63	1.53
6	About Z - axis	1.3827E10	0.765E8	13.44	2.14

A9

Annexure A9: List of Drawings: General Arrangement and Computer Models (9drawings).

6.0 ANNEXURES

1. Computer outputs : As per TABLE - 11.

2. Drawings :

TCE-G18-153-GA- 1000 : General arrangement
TCE-G18-153-SK- 5010-R0 : Cradle structure space truss model
TCE-G18-153-SK- 5011-R0 : Quadripod computer model sh - 1
TCE-G18-153-SK- 5012-R0 : Quadripod computer model sh - 2
TCE-G18-153-SK- 5013-R0 : Quadripod computer model sh - 3
TCE-G18-153-SK- 5014-R0 : Quadripod computer model sh - 4
TCE-G18-153-SK- 5015-R0 : Back structure computer model sh - 1
TCE-G18-153-SK- 5016-R0 : Back structure computer model sh - 2
TCE-G18-153-SK- 5017-R0 : Back structure computer model sh - 3
TCE-G18-153-SK- 5018-R0 : Back structure computer model sh - 4
TCE-G18-153-SK- 5019-R0 : Lightning arrester support computer model

Annexure A10: List of 129 drawings of structural and mechanical parts of the 45m dishes of the GMRT for fabrication and erection.

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LIST OF 129 drawings of the 45m dishes of the GMRT

	45 m Antenna GA	1000	17.
	As.Bearing Arrangement	1012	75.
	Az. Bearing Dust Cover	1028	128.
	Az.Brg.Bottom Support Ring	1022	61.
	Az.cable wrap assly.	1006	68.
	Az.Cable Wrap Details Sh.4 of 4	1044	25.
	Az.Cable Wrap Details Sh.1 of 4	1044	22.
	Az.Cable Wrap Details Sh.2 of 4	1044	23.
	Az.Cable Wrap Details Sh.3 of 4	1044	24.
	Az.drive	1001	129.
	Az.Encloder assly.	1016	73.
	Az.Encoder Details Sh. 3 of 3	1024	40.
	Az.Encoder Details Sh. 1 of 3	1024	38.
	Az.Encoder Details Sh. 2 of 3	1024	39.
	Az.Lock Assly.	1010	76.
	Az.Lock Details Sh 1 of 2	1026	31.
	Az.Lock Details Sh. 2 of 2	1026	32.
	Az.Pinion (With hold on bore dia)	1025	18.
PRF	Back Structure Front Face ?	6102	2.
	Back Structure Hub & Rim Details Sh	6118	15.
	Back Structure Hub & Rim Details Sh	6119	16.
	Back Structure Member Lengths	6107	6.
	Back Structure PRF Type I	6103	3.
	Back Structure PRF Type II	6104	4.
	Back Structure PRF Type III	6105	5.
PRF	Back Structure Rear Face	6101	1.
	Back str. detail of bracing	6240	110.
PRF	Back Str.Fab details of PRF Type II Sh.1	6230	42.
	Back.Str.Fab.details of PRF Type II Sh.2	6231	43.
	Back.Str.Fab.details of PRF Type II Sh.3	6232	44.
	Back.Str.Fab.details of PRF Type II Sh.4	6233	45.
	BOM cradle	6310	123.
	BOM Lightning Arrestor	6288	122.
	BOM Quadripod (9 Shts)	6286	121.
	Cage supporting truss fab.dtls	6287	124.
	Cradle	6111	10.
	Cradle Fab dt. Sh 1	6305	116.
	Cradle Fab dt. Sh 2	6306	117.
	Cradle Fab dt. Sh 3	6307	118.
	Cradle Fab dt. Sh 4	6308	119.
	Cradle Gen.Arrt. Sh 1	6300	111.
	Cradle Gen.Arrt. Sh 2	6301	112.
	Cradle Gen.Arrt. Sh 3	6302	113.
	Cradle Gen.Arrt. Sh 4	6303	114.
	Cradle Gen.Arrt. Sh 5	6304	115.
	Cradle Member Lengths	6113	11.

→ 2

②

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Details of PRF Type III Sh.5	6239	109.
Elevation drive (sn 2/2)	1036	125.
El. drive system	1003	83
El.Bearing Assembly	1002	76.
El.Brg.Details Sh. 2 of 3	1030	34.
El.Brg.Details Sh.1 of 3	1030	33.
El.Brg.Details Sh. 3 of 3	1030	35.
El.CAble Wrap assly.	1017	72.
El.Cable wrap dtls.	1042	74.
El.Drive Details Sh.1 of 1	1036	41.
El.Encoder Assly.	1021	71.
El.Encoder Details Sh.1 fo 2	1031	36.
El.Encoder Details Sh.2 of 2	1031	37.
El.Pinion (With hold on bore dia)	1041	19.
El.Stow Lock Assly.	1009	69.
El.Stow Lock Details Sh.1 of 5	1038	26.
El.Stow Lock Details Sh.2 of 5	1038	27.
El.Stow Lock Details Sh.3 of 5	1038	28.
El.Stow Lock Details Sh.4 of 5	1038	29.
El.Stow Lock Details Sh. 5 of 5	1038	30.
Fab.details of hub	6200	86.
Fab details of hub Sh 2	6201	87.
Fab. details of hub Sh 3	6202	88.
Fab. details of hub Lightining arresstor.	6285	94.
Fab. details of hub back str. PRF type I Sh 1	6225	90.
Fab. details of hub back str. PRF type I Sh 2	6226	91.
Fab. details of hub back st. PRF type I Sh 3	6227	92.
Fab. details of hub back st.PRF type I Sh 4	6228	93.
Fab. details of hub Sh 4	6203	89.
Fab. details of Yoke Sh-5	6329	105.
Fab. details of Yoke Sh-6	6330	106.
Fab. details of Yoke Sh-7	6331	107.
Fab. details of Yoke Sh-8	6332	108.
Fab. drawings PRF TYPE II Sh-5	6234	96
Fab. drawings PRF TYPE III Sh-2	6236	98.
Fab. drawings PRF TYPE III Sh-3	6237	99.
Fab. drawings PRF TYPE III Sh-1	6235	97.
Fab. drawings PRF TYPE III Sh-4	6238	100.
Fab. drawings Yoke Structure Sh-1	6325	101.
Fab. drawings Yoke Structure Sh-2	6326	102.
Fab. drawings Yoke Structure Sh-3	6327	103.
Fab. drawings Yoke Structure Sh-4	6328	104.
Fab.details of rim Type I Sh.1	6250	46.
Fab.details of rim Type I Sh.2	6251	47.
Fab.details of rim Type II Sh.1	6252	48.
Fab.details of rim Type II Sh.2	6253	49.
Fab.details of rim Type III Sh.1	6254	50.
Fab.details of rim Type III Sh.2	6255	51.
Fab.dtls Cradle Sh.5	6309	120.
Feed cable wrap system	1018	84.
Feed drive system Sh 1/2	1005	81.
Feed drive system Sh 2/2	1005	82.
Feed Support Structure	1060	21.
Feed System	1019	20.
Feed.drive system Sh 3/4	1062	85.
Feed.Drive System Sh 2 of 4	1062	64.

PRF

hub

Yoke

PRF

PRF I Fab drgs 2

← 3

Feed.Drive System S? 4 of 4	1062	62
Feed.Drive System S?.1 of4	1062	63.
General Notes	6000	126.
Legs 1 & 1 x Marking plans Sh.1	6276	53.
Legs 1 & 1 x Marking plans Sh.2	6277	54.
Lightening Arrestor	6117	14.
List of Member Sections	6116	13.
Mounting Bracket for Wind Anemometer (with hold)	1020	67.
Quadripod fab.details Sh.1	6278	55.
Quadripod fab.details Sh.2	6279	56.
Quadripod fab.details Sh.3	6280	57.
Quadripod fab.details Sh.4	6281	58.
Quadripod fab.details Sh.5	6282	59.
Quadripod fab.details Sh.6	6283	60.
Quadripod fab.details Sh.7	6284	61.
Quadripod legs 1 & 1 x Key one line drg. quadripod	6275	52.
Quadripod Member Lengths	6110	9.
Quadripod Sh.1, Cage Supporting Truss	6108	7.
Quadripod Sh.2 Member Sections	6109	8.
Rope truss mesh attachment Sh 2/4	1014	78.
Rope truss mesh attachment Sh 3/4	1014	79.
Rope truss mesh attachment Sh 4/4	1014	80.
Rope truss mesh attachment Sh.1/4	1014.	77.
Rope truss mesh attachment Sh 5/5	1014	127.
Rope Truss & Mesh Attachment Gadget Details 33 sheets	1070	66.
Theodolite mount	1004	130.
Yoke Structure	6114	12.

:SORT.A1p:Extra Work .

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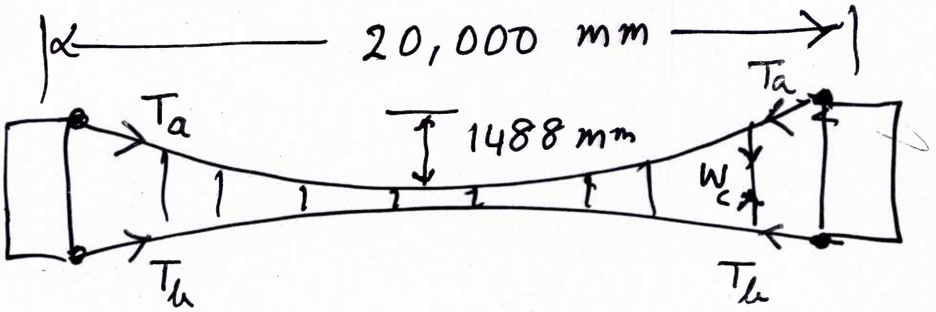
1/2

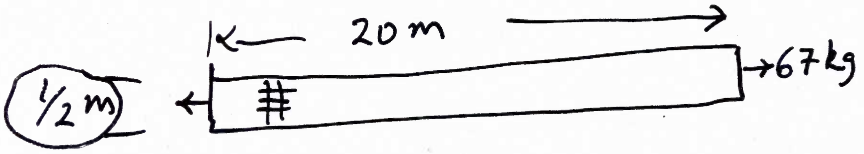


①

SAG (mm)	V=0	V=150 kmph front wind	 Rear wind
FRONT WIRE	1488 mm	1507 (+19) mm	1466 (−22
BACK WIRE	1486	1466 (−20) mm	1508 (+22)

②

TENSIONS	V=0 T (kg)	V = 150 kmph front wind T (kg)	 rear win T(kg
Front Wire	67	109	20
Link Wires (W_c)	2	0.7	3
Back Wire	63	22	110



Tensions given apply load on parabolic frames every 0.5 m apart

A11 : ORIGINAL SCHEME FOR SMART SUGGESTED BY G. SWARUP BUT NOT PREFERRED BY TCE
(See p.2 for EQUATIONS) G.S

Three Basic Equations determine the behaviour of "wire-rope-concept" antenna

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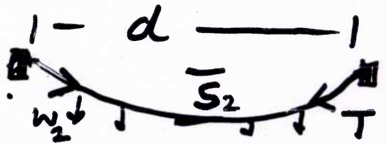
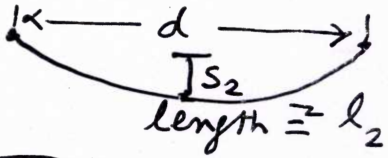
(1) sag $s_2 = \frac{W_2 d^2}{8T_2}$



W_2 = load/m
T_2 = tension

(2) Length of parabolic curve

$$l_2 = d + \underbrace{\frac{8s_2^2}{3d}}_{\boxed{= 30\text{cm for } S = 1.5\text{m},\ d = 20\text{m}}}$$



(3) Under tension T_2 wire strectches

$$l_2 = l_0\left(1 + \frac{T_2}{AE}\right)$$; A = cross-section of wire
E = Young's Modulus

$$= l_0 + \underbrace{l_0 \frac{\sigma}{E}}_{\to \boxed{\sim 25\text{mm for } l_0 = 20\text{m}}} \leftarrow \text{allowable stress}$$

Eliminating l_2 + T_2, we get

$$s_2^3 - \frac{3d}{8}(l_0 - d)\,s_2 - \frac{3d^3 l_0 W_2}{64AE} = 0$$

or $$s_2^3 + a s_2 + b = 0$$

In the above equation $l_0 = \frac{(d + 8s_1^2/3d)}{(1 + W_1 d^2/8AES_1)}$