ANU's new 500 m² paraboloidal dish solar concentrator

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ABSTRACT

The Australian National University (ANU) has worked for many years on paraboloidal dish solar concentrators and demonstrated a 400m^2 system in 1994. The commercialization of this technology has involved a re-design of the Big Dish concept for mass production. The new design is a 494 m² concentrator with 13.4 m focal length and altitude-azimuth tracking. It uses 380 identical spherical 1.17m × 1.17 m mirror panels, which incorporate the Glass-on-Metal Laminate mirrors. Construction of a first prototype on the ANU campus began in the first quarter of 2008. The first on sun test was carried out on 29 June 2009.

INTRODUCTION

The way that modern society meets its energy needs is undergoing rapid change. The main driver for this change is the almost universal recognition that greenhouse gas emissions from the combustion of fossil fuels are beginning to have major impacts on the earths climate systems. Global agreements to reduce emissions and corresponding actions in Australia are now seen as inevitable and essential. In addition to this, there is a consensus amongst industry players that oil, the single most important fossil energy source for the world economy, has reached the point where demand is likely to exceed supply and consequently costs will continue to rise and use-age must ultimately decline in coming decades as reserves are consumed.

This paper describes a unique dish solar concentrator that has been designed to play a role in future sustainable energy supply. It is the third "Big Dish" (Figure 1) concentrator produced by ANU and has been completely re-designed for cost effective manufacture in a commercial context. In this context a light weight structure is an essential need for cost effectiveness and sustainability. The new dish is the biggest of its type in the world and has an aperture area of approximately 500m^2.

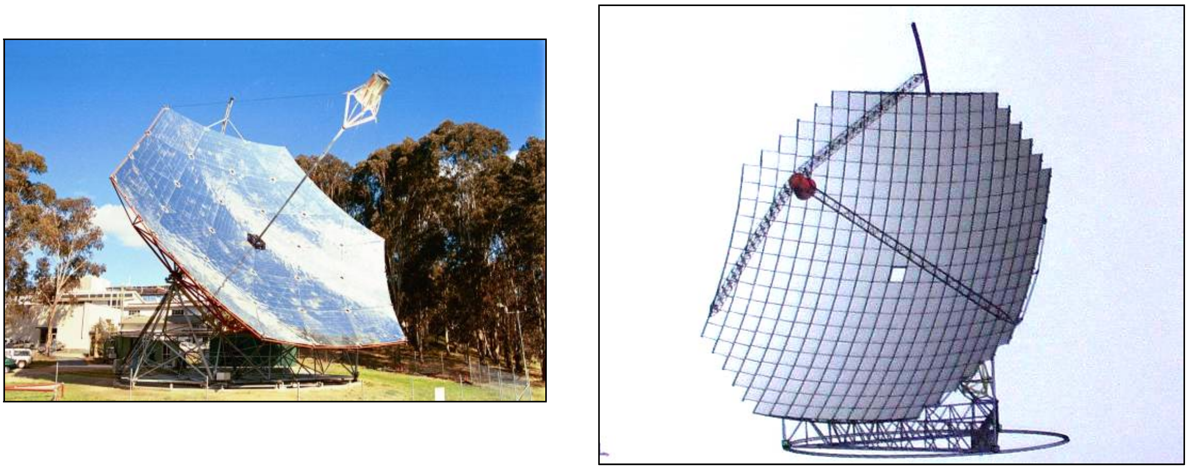

Fig. 1. The existing SG3 400m2 dish (left) and a CAD image of the new 500m2 SG4 dish at approximately the same scale.

SUSTAINABLE ENERGY AND CONCENTRATING SOLAR THERMAL SYSTEMS

The good news is that there are sustainable technologies that are capable of replacing fossil fuel usage and their level of technical and commercial development is more advanced than many in the community realize. Three key technologies are likely to form the back bone of a future renewable energy economy; large wind turbines, Photovoltaic cells and Concentrating Solar Thermal systems. The first two of these are already industries with annual turnovers in the many 10s of billions of dollars and with consistent growth rates in excess of 20% for the last two decades. The Concentrating Solar Thermal field has been quiet for some time, but has begun a period of rapid growth in the last 3 years. It is this field which has potential to be of most interest to the proponents of light weight structures.

Concentrating Solar Thermal systems involve arrangements of mirrors that track the movement of the sun and focus it to a point where the energy is collected at high temperatures in a fluid such as steam that can then be used for power generation. There are three key approaches to this. Tower systems have the energy conversion taking place at the top of a large tower which is illuminated by a large field filled with mirrored heliostats which all move independently to keep the solar radiation focused at the fixed point. Trough systems use a parabolic trough shaped mirror that can be hundreds of metres long. The trough tracks from East to west to follow the sun, which is focused to a central tube containing the fluid. Dish systems are very similar to parabolic satellite dishes or radio telescopes in geometry. The surface is mirrored and they track the sun in two dimensions and focus it to a single spot where a receiver transfers the energy to the fluid. Dish systems would be deployed in arrays of hundreds or thousands of similar dishes arranged in a grid and all sending superheated steam to a central turbo generator plant. In such a context each dish of the new design presented here would contribute around 100kW in electrical capacity (enough for 100 efficient homes).

The systems needed for meeting a significant portion of our energy needs are enormous and require huge capital investments. A Concentrating Solar Thermal power station big enough to replace a major coal fire station and power a major city could occupy an area of the order of 5km x 5km. It is thus essential to drive costs down as much as possible. This immediately suggests the need for light weight smart structures that support the mirrored surfaces with as little use of materials as possible. Aside from the cost issue, if the technology is to be a truly sustainable option its use of materials must be such that the time taken to recoup the energy needed for manufacture is a small fraction of a system lifetime.

HISTORY

The ANU has worked on dish concentrator systems since the early 1970's. Early work lead to the construction of the White Cliffs solar thermal station with fourteen $20m^2$ dishes. A key lesson learnt was that larger dishes would be more cost effective. The ANU Big Dish design has two previous working prototypes. The 400 m^2 prototype (SG3) was completed in 1994 and successfully proved the technical viability of a concentrator that is approximately 3 times bigger than any other produced (1)(2). A subsequent similar system provided to the Ben Gurion University in Israel.

The previous big dish structures are based on a space-frame design. Altitude / Azimuth tracking operation is used, with the dishes rotating on reinforced concrete tracks, with a base frame supported by wheel assemblies. The ANU prototype, delivers a peak concentration ratio of 1500 times natural sun intensity (3). On the ANU campus dish, a monotube boiler housed in a "top-hat" cross section cavity receiver produces steam that is superheated at up to 500°C at 4.5 MPa. This steam is passed to the ground via an insulated steam-line and rotary joints. Dish receivers of this nature can provide steam at any temperature and pressure that commercially available steam turbines can work with.

The space frames for both previous dishes have been assembled with “Octalok” Technology. In the early 1980’s, an Australian space frame system, Oktalok, was developed by Geodome Space Frames, a Melbourne company. Oktalok was modelled after the renowned Mero system, from which had sprung a plethora of ball and tube style systems around the world, following the end of patent protection on Mero. In this case the Oktalok system for bolting was its main difference and patentable processes were developed, based upon use of high strength SCHS fasteners, inserted into the tube through a keyhole access port, close to the end of each member. Geodome directors, Robert Barrow and David McCready held the ambition to produce a system of equal structural performance to that of the famed Mero, but with higher finish specifications, if possible. All members were hot dipped galvanised inside and out after all fabrication to preserve the anti corrosion coating. A wet spray, three stage, polyurethane paint coat was given to all members after the galvanised surfaces had been linished to remove roughness and porocity.

The ball and strut system allows a high order of practicality in structure, being capable of joining a relatively dense array of members in three dimensional space from any direction. Other connector systems are not as effective in that respect. Its aesthetics, given the short itinerary of parts, is of a high order. To enhance the impact of the spherical connectors, a Marine grade duplex nickel coating was given to all nodes after linishing, then a chrome flash to produce a shining surface seal. This proved durable in exposed conditions over the long haul. Unbrako bolts were used for fasteners. Structures were built in most major cities of Australia and a large number were constructed in south east Asia.
For the two previous dishes the accuracy and versatility of Octalock allowed a one off prototype to be assembled with minimal infrastructure but with high accuracy achieved in the paraboloidal shape.

In 2005, ANU dish technology was licenced exclusively to the Canberra-based company Wizard Power Pty Ltd. In collaboration with ANU, Wizard Power secured support under the Australian Government Renewable Energy Development Initiative (REDI) program, for a project that included the design and demonstration of the second generation Big Dish, suitable for commercial production, which is described in this paper.

ESTABLISHING THE FUNDAMENTALS

The new dish design, has been developed by a joint ANU / Wizard Power team starting from first principles. The mission was to design a large-area solar dish to produce energy at minimum installed cost, when mass produced on a large scale. Additional customer requirements including minimising technical risk and maximising reliability. Being attractive to investors, ease of operator training and applicability to a range of energy conversion options, were considered.

An analysis of normalised dish cost per unit aperture area as a function of dish radius has been carried out previously (2). , and supports a choice of most cost-effective size between 400 m² and 1000 m².

A range of basic geometries for the dish tracking structure were considered, including, polar-equatorial, altitude-azimuth with high pivots, SG3-type geometry, pedestal-mounted altitude-azimuth and a range of novel approaches. These were assessed against cost and other selection criteria according to their impact on structure, actuation systems and overall performance. Whilst a number of options were rejected outright, the remaining options were found to have comparable cost performance to the SG3 geometry, so the overall geometry of this earlier design has been kept.

DESIGN DEVELOPMENT

The design process followed rigorous systems-design principles and carefully considered the interactions between the key subsystems of structure, mirrors, receiver, foundation, and actuation, as each was developed in parallel. With the exception of the size and overall altitude – azimuth tracking geometry, virtually every aspect of the design has been changed over the SG3 dish.

After evaluation of options, it was considered that cheaper approaches than Octalock could be found for situations where many duplicate unites are to be made. The new design instead incorporates a very accurate re-useable jig, to provide the accuracy of the frame supporting the optical surface. Novel fabrication techniques have been employed to form the space-frame on this jig in a manner that is rapid and cost-effective. The emphasis is to establish a 'Factory-in-the-Field' concept for manufacture of large dish arrays. A key element of this is the on-site production of roll-formed structural sections from steel coil stock.

‘Microstran’ software was used to analysis forces in frame elements, ‘Strand’ was employed for analysis of stresses in key elements, and ‘SolidWorks’ was used to visualize overall construction and to produce working drawings.

Mirrors were identified as a key driver for the design. A Glass on Metal laminate approach using thin low iron back silvered glass mirrors had previously shown to be a durable and effective approach. For dish mirrors, forming into multilayered cored panels has proved to be an effective way of producing shapes with good optical quality. Previous studies (4) indicated that a dish could be built with good optical performance using standard spherical element mirror panels which would suit mass production. Materials, optical and structural constraints were reviewed to choose a square rather than triangular unit and to determine an optimum unit size. It was identified that the stiff panel design needed for optical quality meant that there was an opportunity to leverage this to a contribution to the overall dish structure. Such an integrated approach is key to a cost optimized outcome.

Wind loads were a major driver in determining the structural design. The appropriate structural design code for Australia (5) identifies ultimate limit state wind speeds based on location, height and other factors. The actuation geometry taken from the SG3 design, has the dish parked horizontally for maximum storm survive-ability. For the parked dish height chosen, a 162kmh limiting wind speed was indicated.

The assumption that some form of space frame would be needed was made early in the process. Based on this a review of the cost effectiveness of various material approaches to supporting an indicative load over a 3m span was carried out. Interestingly, wood or reinforced concrete were shown to be most cost effective but deemed impractical. Aluminium or galvanised steel tube sections were shown to be almost identical in cost effectiveness. Steel was chosen based on the wider applicability of fabrication techniques for large structures.

The SG3 dish employs a tetrahedral element space frame as this is the most structurally efficient modular unit. The potential to use mirror panels structurally however, converts the entire front surface of the dish into a membrane. This being so, either a tetrahedral or square pyramid space frame unit performs equally well for the rest of the structure. Square pyramid was chosen for easier coupling to a mesh of square mirror panels.

The specifications of the new dish are:

Aperture	494m2
Focal length	13.4m
Average diameter	25m
Average rim angle	50.1o
Mirror reflectivity	93.5%
Number of mirrors	380
Mirror size	1165mm x 1165mm
Total mass of dish	19.1t
Total mass of base and supports	7.3t

STEPS IN CONSTRUCTION

Construction of a first prototype (designated *SG4*), by ANU personnel, on a site immediately adjacent to the existing SG3 dish on the ANU campus, began in the first quarter of 2008.

Fig. 2. Construction of the dish frame forming jig from a series of trusses.

Site works began with the preparation of a concrete slab slightly bigger than the 500m^2 aperture of the dish. This slab was designed to provide a stable surface for the assembly of the dish frame jig. For the SG4 prototype, the slab was subsequently re-used as the foundation for the dish itself. The intention for the construction of a commercial dish array, is that a single slab would be established for the jig, in the middle of the intended array, with dish frames then produced in sequence and transported short distances to their individual locations.

The jig is formed of a series of parabolic trusses as shown in Figure 2. These were screwed to the concrete slab and linked together to form a paraboloidal dome. A series of adjustable supports were attached to the truss tops, forming a square pattern in plan view that roughly correlates with the mirror vertices. Photogrametric measurements based on photographs taken from a box suspended from a crane and positioned at locations around and above the jig, allowed accurate determination of support positions. Iterative measurement and adjustment brought the supports to an average error of +- 0.4mm from the true paraboloid.

The dish frame was formed in two stages. Initially a front surface made up of “top hat” cross section steel members running in two directions to form an approximately square mesh, as seen in

Figure 3, was positioned on the jig supports and riveted together using a self piecing riveting system. These top hat section members were themselves formed on site using a custom built section rolling machine that rolled them continuously from sheet metal coil stock. This rolling process also imparted a curvature equal to the average radius of curvature of the dish, so that elastic conformance to the jig was obtained with modest hold down forces. The advantage of on site forming using a containerized plant, is that it is not necessary to transport cumbersome long shaped structural members long distances.

The second stage of the process (shown in Figure 4) involved the attachment of a series of pyramid forms made from Circular Hollow Section galvanized steel. These pyramids were themselves pre-fabricated using a process of squashing their ends to a structurally optimized taper and welding to plate nodes. Pyramids were attached to span 3 x 3 cells across the surface structure. Once fixed, extra members were used to tie the pyramid vertices together and so form a complete space frame. Figure 5 shows the completed dish frame being lifted off the jig. In this lifting process it was turned over and rested on the ground pending the construction of the base-frame.

Fig. 3. Front surface of in-situ rolled sections joined in a square lattice by self piercing rivets. Prefabricated pyramid structural elements in the foreground.

Fig. 4. Dish frame with pyramids installed and back surface chords being welded in place.

With the dish frame complete, the jig was removed for re-use by Wizard Power at another location. A steel Azimuth tracking ring was installed to the slab, a pre-fabricated base-frame installed and the dish frame lifted in and installed to pivots and actuators as shown in Figure 6. The base-frame is formed from three trusses joined to form a triangle. A wheel block at each vertex of the base-frame triangle supports the dish and allows Azimuth movement. The wheel blocks both support the dish and also incorporate engagement with the beam to resist overturning moments in strong winds.

Fig. 5. Removal of the completed dish frame from the jig.

Fig. 6. Dish frame assembled on base-frame, with actuation systems in place.

FABRICATING AND INSTALLING MIRRORS

For the prototype, all the mirror panels were fabricated by hand in the ANU workshop. Figure 7 shows the mirror panel installation process underway. A system of wooden decking across the dish surface allowed personnel to work across the surface safely. Mirror panels were positioned and bonded along two edges to the top hat front surface sections forming the upper most layer of the front surface structure. As each panel was laid, the decking piece under it was subsequently withdrawn for use at another location. Panels were covered with plastic sheets to protect against unwanted reflections during the installation proves.

Fig. 7. Early stages of mirror installation on the dish surface.

Small wedge shaped gaps appear between adjacent panels along a row as the square panels are packed to conform with the paraboloid. Figure 8 shows the dish with all panels installed, viewed from behind.

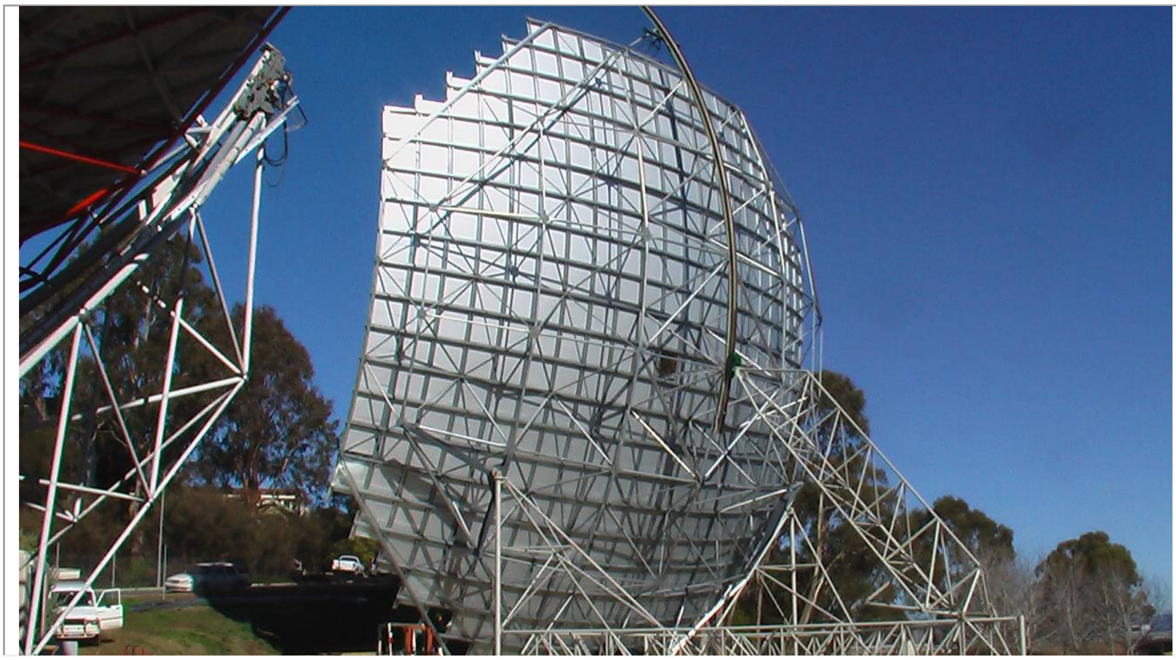

Fig. 8. view of the completed dish from behind in the fully elevated position.

BALANCE OF SYSTEM

Electric drive was chosen over the hydraulic system used on the SG3 dish after a review of costs. AC motors coupled to reduction gearboxes are used. Elevation is achieved with a motor gearbox unit driving a pinion on a machined rack attached to curved back-beam fixed to the back of the dish frame. Azimuth drive uses an identical motor gearbox unit directly driving one of the wheels. The reduction of 400:1 in the gearboxes is insufficient for continuous tracking so intermittent operation is used.

A tetrahedral receiver support system was fabricated and installed in parallel with the mirror installation. The three legs are light weight trusses optimized to minimize shading. They have been designed to support a receiver unit up to 2,000kg in weight. The three legs terminate at a large cylindrical structure that is designed as a "plug in" port for a range of different receivers that are likely to be used into the future.

ASSESSING PERFORMANCE

Fig. 9. First test of the dish on sun, 29 June 2009.

Figure 9 shows the first on sun operation of the dish on 29 June 2009. It can be seen that the wooden decking remained in place where mirror panels had not been yet installed around the periphery of the dish.

Fig. 10. Zoomed in view of the flux mapping target through neutral density filters.

The key performance criteria for a dish solar concentrator is the degree of concentration as indicated by the size of the sun image produced. The level of concentration is indicative of the degree to which the structure is accurately conforming to the desired paraboloidal shape. This is typically assessed by photographing the image on a heavily cooled plain target. Figure 10 illustrates this process during the first test. The new dish has achieved very satisfactory levels of concentration, so much so that full moon imaging was employed instead as the targets used for full sun flux mapping were all destroyed by the high flux levels. Results obtained to date indicate that 95% of the radiation can be captured within an aperture of 500mm diameter, with an average concentration slightly in excess of 2000 times sun intensity. Within this the highest peak in the centre exceeds 10,000 times. The significance of this is illustrated by the fact that in a scan lasting just a few seconds the peak flux has rapidly melted ceramic blanket insulation material with a 1400°C melting point.

Figure 11 shows the completed dish under operation during the first test with all the mirror panels uncovered.

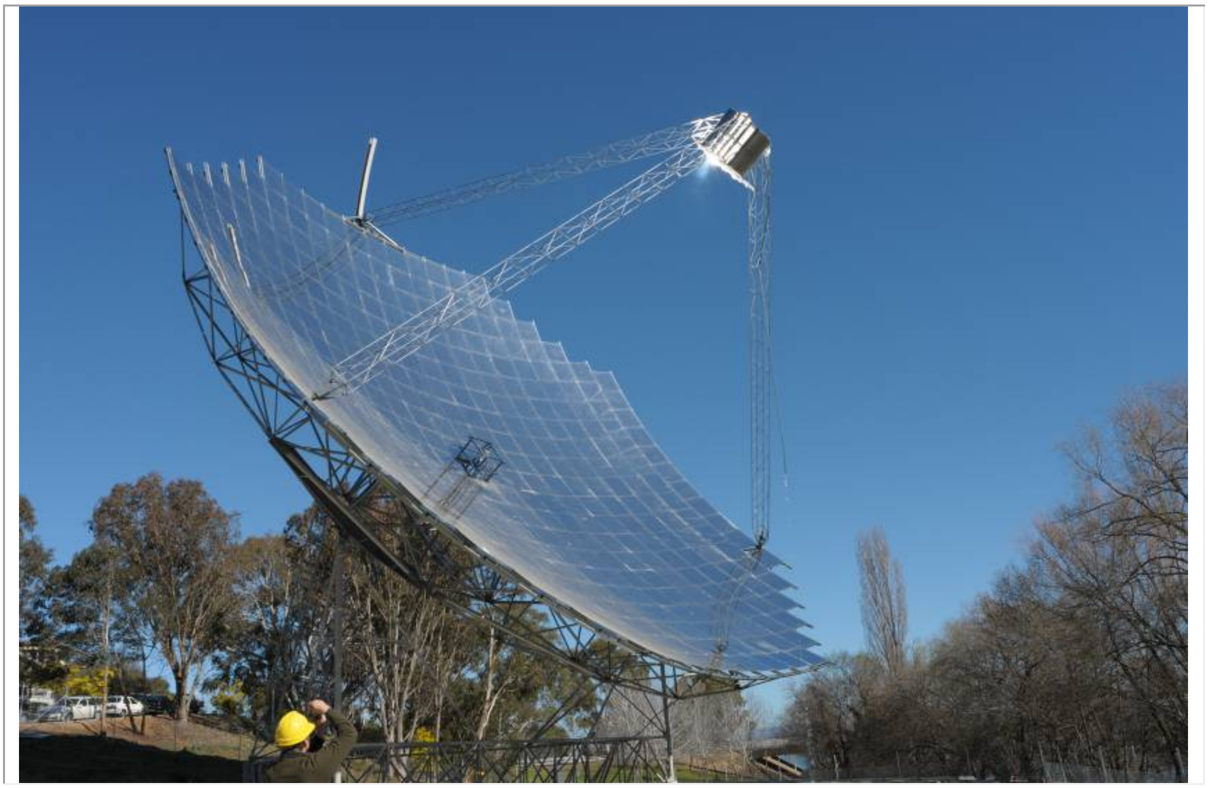

Fig. 11. First on sun tests with all mirrors uncovered

MOVING FORWARD

A range of further investigations are planned to test the new dishes' optical performance. Photogrammetric measurements of the completed concentrator surface will be conducted. The dish will then be used as a research tool to investigate energy conversion via direct steam generation, thermochemical processes for fuels and energy storage and small (Brayton) turbine cycles among others.

In parallel with this, Wizard Power has commenced construction of a pilot system of 4 such dishes in Whyalla in South Australia. Once this system has operated successfully, the hope is to proceed to full commercial power stations in the near future.

CONCLUSION

The large dish approach to solar concentrator systems offers the highest possible conversion efficiencies and justifies the higher capital cost per unit area. ANU has worked for many years in this field and is in the final stages of construction of a new 500m^2 unit that is a prototype of a design optimized for manufacture. The construction of the prototype and successfully proven a range of novel design features including the use of the mirror panels to form part of the structure itself. This paves the way for construction of commercial arrays.

ACKNOWLEDGEMENTS

The financial support provided under the Australian Federal Government's Renewable Energy Development Initiative program is gratefully acknowledged.

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