Low-Cost, Open-Source, Collapsible, Air-Transportable, Field-Manufacturable Telecommunications Tower

Gregory Stevens, David Ilba, Stuart Wildy, Paul Gardner-Stephen.
Flinders University,
Adelaide, Australia.

Matthew Lloyd
New Zealand Red Cross,
Wellington, New Zealand.

***Abstract*—Temporary telecommunications systems are often deployed in humanitarian situations. Such systems typically require or operate more effectively with the antennae elevated above surrounding structures, maximizing line-of-sight coverage. Achieving this elevation for all deployments is problematic for several reasons.**

First, chartered or scheduled commercials airlines continue to play a prominent role in delivering relief personnel and equipment during the acute phase of many disasters and related events. This places limits on the size and weight of equipment that can be delivered during this critical period.

Second, any repairs or modification to equipment must rely on limited local resources, and thus it is desirable for equipment to be constructed of common building materials.

Third, weather conditions are often poor, requiring structures to be sufficiently strong. This stands in tension with the desire that the equipment be as low-cost as possible to maximize the number of units that can be deployed.

In this paper we describe a low-cost, portable, airline luggage compliant, collapsible telecommunications tower designed as a student project that meets various Australian standards, can be easily erected in seven minutes and costs less than US$600 in small quantities, and for which all custom parts can be 3D printed in the field. A prototype of this tower weighs just 19kg, and survived a 30-day deployment, including winds up to 22m/s (80km/hour), and is rated to survive much stronger winds. The designs for this tower have been open-sourced for replication and use by any party.

Keywords—telecommunications; serval project; humanitarian; disaster relief.

I. INTRODUCTION

The need for effective communications arises in a wide variety of contexts. While the circumstances differ greatly – including disaster response, isolated communities, mass gathering among others – the needs are often remarkably similar.

For disaster response, portable and lightweight communications infrastructure reduces the logistical challenges involved in restoring communications. For isolated and transient communities and work forces, affordable, portable and easy to erect communications towers can help these communities to keep in contact. Making the designs free and open, and using common and easily manufactured parts benefits both of these use-cases by enabling maximum adoption and future innovation. Finally, for mass-gatherings such as music festivals can benefit from similar characteristics. Music festivals and concerts in Australia often move between cities with only a day or two between successive events, making rapid erection and air transportability desirable.

It was reflection of this alignment of requirements among these various use-cases that bought the authors together to seek the creation of an robust, open source, light-weight, easily manufactured, easily erected and transportable as ordinary airline baggage communications tower design. The interests include disaster response and in isolated and difficult situations (New Zealand Red Cross, the Flinders University Resilient Communications Laboratory and Serval Project), and provision of wireless communications at music festivals (Gregory Stevens and David Ilba).

The remainder of this brief paper describes the design, prototyping and initial testing of the Open-Source Collapsible Communications Tower as part of a student project, briefly addressing the requirements for replicating the tower, and future plans. These and other topics are covered in more detail in [1].

II. DESIGN CONSIDERATIONS

Exploring the various use-cases resulted in the enumeration of a number of requirements and constraints that were applied during the design process.

1) Electrical, Radio and Practical Requirements

The design was created with the goal of supporting small, low-cost, lightweight, radio transceivers, such as those being designed by the Serval Project [2 – 6]. Such transceivers typically operate in the 915MHz, 2.4GHz or 5GHz Industrial, Scientific and Medical (ISM) radio bands with a maximum EIRP of 4 Watts. In order to use low cost radio hardware, and avoid transmission losses through long cable runs, the tower must provide an enclosed housing at the top of the tower where the transceiver(s) can reside, and tip sway must be constrained so that moderate gain antennae could be used.

It was also desired that the towers should be tall enough to clear typical single-floor dwellings, and otherwise as tall as practicable to maximize line-of-sight propagation opportunities for the radio transceiver. The towers should also be completely free standing, not depending on any existing structure or infrastructure.

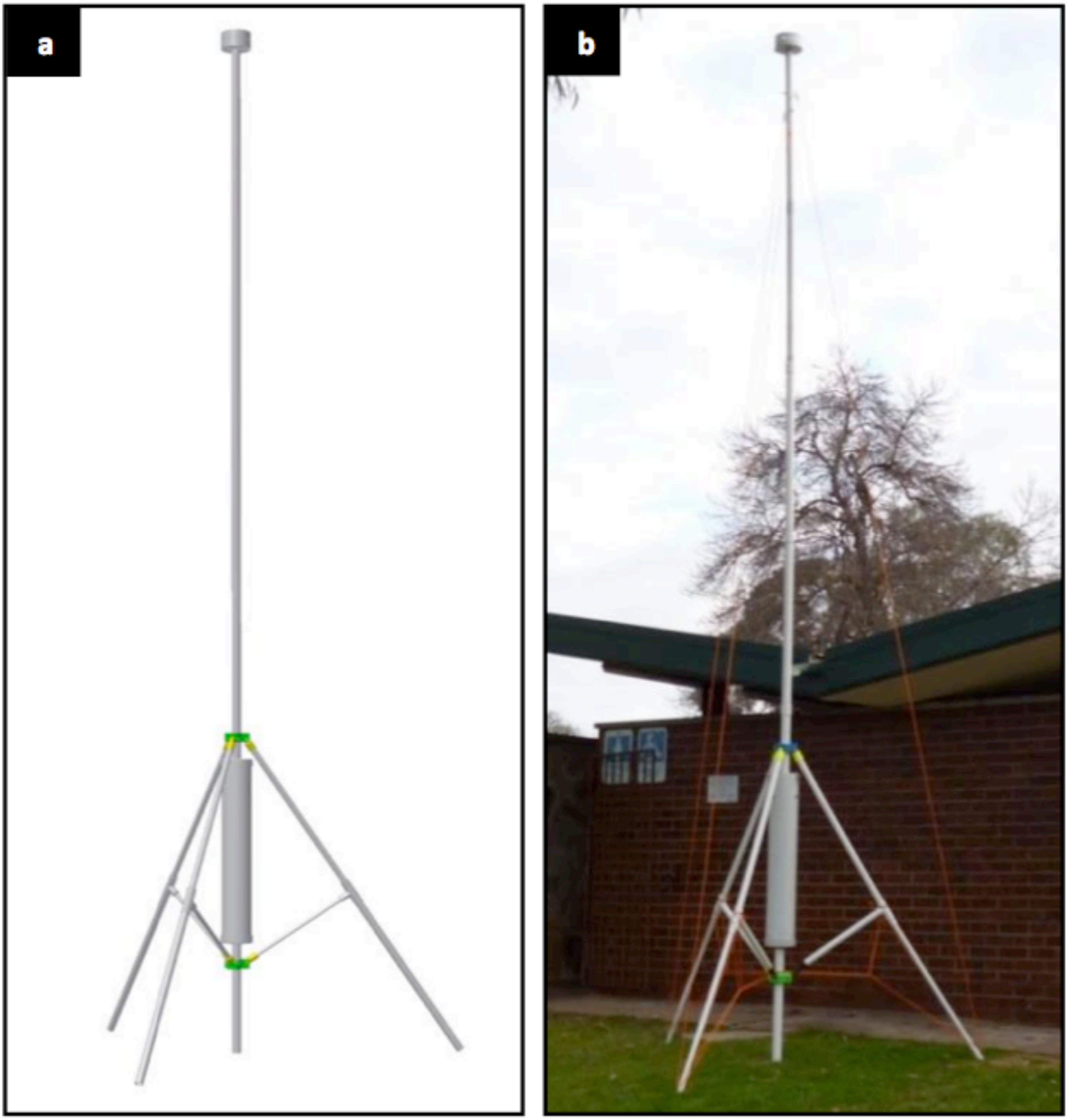

Fig. 1. Tower design (a) and erected prototype (b).

Fig. 2. Unpacking ballast section from carry bag (a), fastening load-supporting leg (b), and filling ballast with water (c).

Reproducibility and sustainability of the design was also desired, in that the design must be cheap to manufacture, and that it should use commonly available hardware components wherever possible, and be easily repaired in the field with limited resources. Any custom parts should be printable with a commodity 3D printer so as to minimize the barrier to manufacture by any party. Finally, the resulting design must be released under an open-source license to facilitate replication and permission-less innovation [7]. Through these constraints it is hoped that any resulting design would be practical in disaster response, as well as in isolated and developing contexts.

2) Safety Regulation Compliance

Given that mass gatherings are a target use-case for the design, there are well-documented standards for safety of structures at such events. Examination of these standards has value for the humanitarian use-cases, where failure of relief structures is extremely undesirable. Thus it was appropriate to consider various safety standards used at mass gatherings and seek to ensure that the design complies. The authorities considered include the British Health & Safety Executive's "The Event Safety Guide" [8], and the Australian Entertainment Industry Association's "Employer Guide to OH&S in The Entertainment Industry" [9]. While care was taken to consider the implications of these guides, the design has not been rigorously assessed against them due to the time limitations of the student project process.

3) Standards Compliance

A principal concern was that the design should meet the relevant Australian Standards for communications masts. Review of potentially relevant standards identified the following as having relevance for the design: AS1170.1 (SAA Loading Code, Part 1 – Dead and Live Loads) [10], AS1170.2 (SAA Loading Code, Part 2 – Wind Forces) [11], AS3995 (Design of Steel Lattice Towers and Masts) [12], AS4268 (Radio Equipment and Systems – Short Range Devices) [13] and AS4676 (Structural Design Requirements for Utility Services Poles) [14].

Examination of these standards revealed substantial overlaps, for example AS3995 references both AS1170.1 and

Fig. 3. Mast section coupling (a), assembly (b), and erection with communications payload housing attached (c).

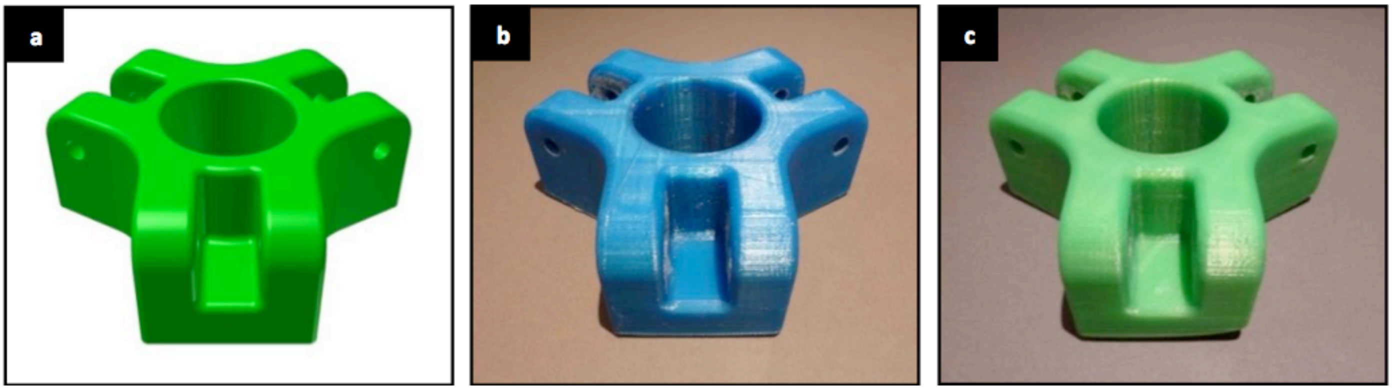

Fig. 4. Tripod bracket CAD design (a), and printed prototypes in PLA plastic (b) and ABS plastic (c).

AS1170.2. The standards also allow simplified analysis if a design satisfies certain assumptions. For example, to be allowed to use these standards to develop engineering specifications, it needs to be assumed that the tower has an equilateral-triangle or square plan lattice structure, with circular or square members. It also needs to be assumed that the force coefficient shall be constant for any inclination of the wind-to-beam-face. These assumptions permit the use of the wind load tables from these standards. The design should therefore satisfy these assumptions.

The tower was designed with summer mass gatherings in Australia as the core use-case to limit the scope of the project. This was necessary as the project was undertaken as a final-year engineering student project. The practical effect of this is that ice, earthquake and incidental loads were not considered during the design process.

Considerable emphasis was placed on ensuring that the structure could withstand high winds. AS3995 defines a number of wind speed zones for Australia. The maximum design wind speed varies according to these areas, ranging from “Normal” to “Tropical Cyclone”. The highest standard, “Tropical Cyclone” was followed, requiring that the design withstand wind speeds of up to 85m/second (306km/hour, 190mph or 165 knots).

AS3995 also provides for discounting or compounding the required design wind speed based on the height of a structure above the surrounding terrain. The structure is designed to stand approximately 6 meters high, and to be ordinarily deployed on the ground. Discounts apply under AS3995 for structures not more than 15 meters above the surrounding terrain. No such discount was taken in the design, allowing the structure to be located on top of an existing structure not more than 9 meters high without de-rating the design wind speed below 85m/s. Similarly, direction-of-wind discounts can also be applied under the standard, but were not during the design of the structure.

Where structures are placed on crests of hills, ridges or escarpments or other similar locations de-rating of the design wind load may apply, but are beyond the scope of this paper. Those considering such deployments should be aware that placing structures near such crests will de-rate the design due to the higher winds experienced at such locations.

AS3995 requires analysis of tower designs using the first-order linear elastic method, including determining the first mode frequency of the structure, which is supported by many finite element analysis (FEA) software packages, simplifying the design validation process.

4) Airline Baggage Regulations

Both the mass gathering and humanitarian use-cases make it desirable to be able to pack a communications tower down to fit into standard airline luggage, so that it can be easily transported on passenger aircraft.

Surveying several major airlines active in Australia, the minimum allowable baggage item was identified to be not more than 140cm linear dimensions, and weighing not more than 20kg. These constraints were applied to the design process. Associated with this, consideration was given to the dangerous goods and other baggage policies that could impact on the design.

III. Prototype Design

Figures 1a and 1b respectively show the design and prototype of the tower. It consists of a PVC monopole surrounded by a ballast tank and tripod structure. Guy ropes were added during the refinement of the design to ensure structural integrity and robustness of the structure. The ballast tank can be easily filled with sand or water, and also doubles as the carry case for all components.

1) Use of common plumbing parts

In keeping with the open-source and accessible design focus of the project, 150mm PVC-DWV pipe was selected as the main component of the ballast system. A 1m section of 150mm PVC-DWV pipe hold both water and sand well, and can also neatly fit the seven 40mm PVC mast sections inside it for transportation.

The ballast can hold approximately 17.6L of water and this provides approximately 173N of ‘live-weight’ force. In order to suspend the ballast between the two sets of tripod legs, a 40mm PVC load-supporting leg was designed to fasten to the bottom of the ballast with a 25mm PVC bush/cap/socket arrangement.

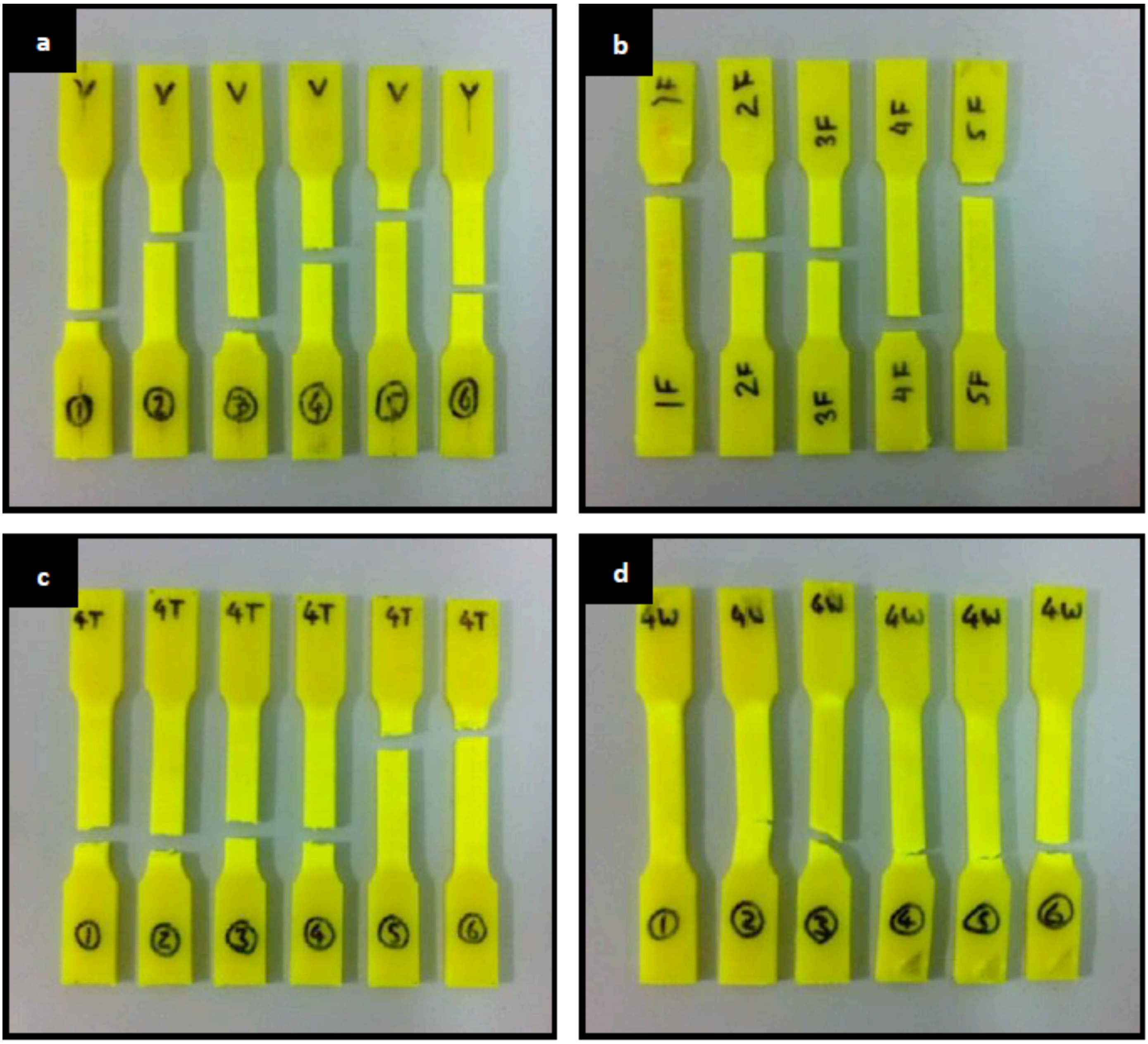

Fig. 5. A. Failed 3D printed dog-bone tensile test specimens. Specimens printed vertically (a), horizontally (b), at 45-degrees across the thickness (c), and at 45-degrees across the width (d).

To strengthen the load-supporting leg, a double thickness of 40mm PVC- DWV- and 40mm PVC-PN pipe (ideal friction fit) were glued together using PVC primer and cement. Lastly, it is important to note that the centroid of the ballast is located at a height of 1.2 meters from the ground. This height is not optimal from a structural perspective, but was necessary to obtain reasonable leg lengths.

Figure 2 shows the assembly and filling of the ballast through the large top opening. The ballast cap is a standard 150mm diameter PCV end-cap.

The core design requirement for the mast was to elevate the Wi-Fi access point or other radio components to a height greater than 6 meters. In addition, the mast needs to anchor on the inside of the ballast, possess minimal tower-tip deflection in winds, and be structurally stable during various impact loads.

To maximize the axial stiffness, the mast was designed from the largest standard PVC pipe diameter possible in order to reduce bending. This meant that a combination of 40mm PVC-DWV and 40mm PVC-PN was used: 4 of 750x40mm PVC-DWV pipes and 4 of 750x40mm PVC-PN pipes. To join the 750mm section, standard 40mm PVC couplers were used, as can be seen in Figure 3. Lastly, the mast was centralized to the inside of the ballast through the re-use of the 25mm PVC cap, used for securing the load-supporting leg.

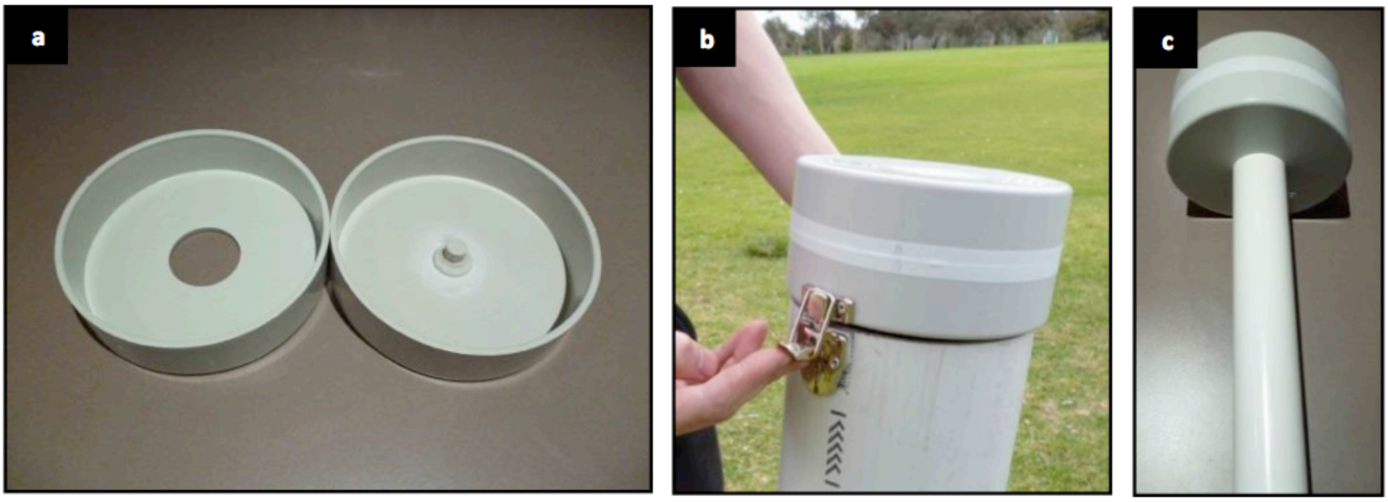

Fig. 6. Electronics housing parts (a), acting as cap to disassembled unit when in transport (b), and mounted to the top of the mast (c).

2) 3D Printed Parts

Keeping the total weight of the tower below 20kg necessitated designing a custom lightweight bracket (figure 4). There were two key design requirements of the tripod bracket: to act as a structurally sound pin-joint for the tripod legs, and to facilitate adjustable leg height through permitting vertical translation along the mast and load-supporting leg. This part was designed for fabrication on commodity 3D printers.

The mechanical properties of the part when produced using a low-cost and relatively portable 3D printer, a MakerBot Replicator 2X 3D [15], were unknown. The tripod bracket was designed to maximize structural strength and durability. This meant that the part was designed with excessively thick pin-joint support struts and was printed with 100% infill.

In order to determine whether these 3D printed parts had the required strength and durability, standard dog-bone specimens (6mm x 12mm rectangular cross-section) were printed using both ABS and PLA (Figure 5), and then tensile tested using an Instron 5969 universal testing system.

Since it became apparent that ABS is a stronger plastic than PLA, worst-case mechanical properties focused on parts printed in PLA. A number of dog-bone samples were then printed out of PLA with different layups, including samples printed horizontally, vertically, at 45-degrees across the thickness and 45-degrees across the width.

Several observations were made upon inspection of the failed specimens. From Figure 5 it can be seen that the horizontally and vertically printed specimens failed at random locations, whilst the angularly printed specimens seemed to mostly fail near the clamping region of the specimens.

It was also realized that the vertically printed specimens failed along a layer of the plastic, whilst the specimens printed at 45-degree angles failed over several layers. We thus concluded that the direction of print layup does not necessarily indicate regions of lower mechanical properties, and that further testing was required to gain a better understanding of PLA's anisotropic properties.

The Instron experimental test results showed that the horizontally printed PLA specimens have the highest average yield stress (38MPa), while the specimens printed at 45-degrees across the width had the lowest (32.6MPa). This is due to the fact that the horizontally printed specimen layers run parallel to the tensile load thus providing the most strength, whereas the layers of the specimens printed at 45-degrees across the width run at 45-degrees to the load, which aligns with the maximum resolved shear stress.

When assessing the Young's modulus, the horizontally printed specimens had the lowest average modulus (2.47GPa), while the specimens printed at 45-degrees across the width had the highest (2.71GPa). In addition the results showed both angularly printed specimens had higher Young's moduli than the vertical and horizontal printed layups, this suggests that the angularly printed layups provide more stiffness.

It should be noted that, since a material property study was not initially planned for the project, nor is it a core project objective, this section has merely provided a general overview of the mechanical properties of Replicator 2X 3D printed parts.

3) Electronics housing

The primary design requirement for the electronics housing is to contain and protect the radio components. The secondary requirement for the housing is to act as a lid to the carry-case, as seen in Figure 6b. To achieve these requirements while still providing a low-cost solution and fitting with the accessible components objective, two 150mm PVC pipe caps were utilized. These caps, located end-on-end have sufficient space to store all the components except for the battery (which will be located on the ground), and are more than capable of protecting the components from moisture and ultraviolet (UV) light.

The housing is attached to the carry-case with two stainless steel latches and is attached to the top of the mast with a 25mm PVC threaded adapter fitting. The housing was attached to the carry-case with two stainless steel latches. Although not shown in Figures 6a & 6c, ventilation and power lead holes were drilled on the underside of the housing. To hold the two halves of the housing together, standard electric tape was used since it provides a low-cost, water resistant solution. Power and network can be supplied to the electronics package through the mast.

4) *Results and conclusions*

Following the construction of a prototype, an informal structural stability and strength test was performed to determine whether the tower could maintain stability and to be free-of-failure after sustaining varying impact loads. Once erected, some of the authors applied impact loads to the structure with varying magnitudes and locations. It was estimated by the team that the loads would have ranged from 1-50N. The analysis found that while the impact loads initially excited the tower, after short periods the vibrations would cease. It was realized that the tower had both sufficient strength to endure impacts and also a large enough footing plan and structural design to ensure that the tower was structurally stable.

The prototype unit was erected and left standing for 30 continuous days in the Adelaide metropolitan area, Australia to assess its' real-life performance. The mast was secured with guys 4 meters from the central axis for the first 14 days, and then with guys terminating on the legs of the structure for the remaining 14 days. During that period winds of up to 80km/hour were logged (Table 1), and the structure had no performance problems.

While compiling the costs of the major Australian hardware store's off-shelf parts simply required time and effort, developing accurate costs for the custom-made 3D printed parts was more challenging. A simple methodology was adopted, combining the material cost (determined by weighing the complete part) and amortization of the 3D printer (1% of machine cost per part printed). Knowing the cost of plastic per kg (48AUD/kg) and cost of the 3D printer (2,900AUD), it was possible to estimate the total parts cost at 301AUD, being 78.90AUD for 3D printed parts and 231.72AUD for the off-the-shelf PVC and other components.

Overall, while further testing and refinement of the prototype is warranted, for example to determine the factor-of-safety and lower the center of gravity of the ballast, we are satisfied that we have created a portable communications tower that can be easily replicated, quickly erected and applied to a variety of humanitarian and other applications. By open-sourcing the design we hope that it can both be used and improved by the community at large. Design files can be downloaded from [16].

TABLE I. TIME SERIES OF WIND SPEEDS DURING TEST

Date	**Wind Speed**		
	Max km/hour	***Direction of maximum wind speed***	***Average km/hour***
16SEP13	50	WSW	20.2
17SEP13	68.4	N	16.6
18SEP13	55.4	WNW	24.5
19SEP13	53.6	WSW	13.3
20SEP13	33.5	WNW	11.9
21SEP13	50	WSW	9
22SEP13	29.5	N	8.3
23SEP13	51.8	NW	15.1
24SEP13	46.4	NW	13.7
25SEP13	55.4	WNW	11.5
26SEP13	81.4	WSW	22.3
27SEP13	55.4	N	15.1
28SEP13	42.5	WSW	13.7
29SEP13	42.5	N	11.5
30SEP13	79.6	NW	17.6
01OCT13	57.2	W	19.4
02OCT13	66.6	W	22.3
03OCT13	35.3	SSW	14.8
04OCT13	40.7	WNW	11.2
05OCT13	50	NNW	13.7
06OCT13	35.3	W	9.7
07OCT13	33.5	W	10.1
08OCT13	31.3	N	17.6
09OCT13	50	N	16.6
10OCT13	51.8	WSW	13
11OCT13	31.3	WNW	9
12OCT13	42.5	NNW	14
13OCT13	63	WSW	16.6

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