METEOROLOGICAL TOWER DESIGN FOR SEVERE WEATHER AND REMOTE LOCATIONS

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ABSTRACT: We have developed a robust meteorological tower for deployment in locations with extreme conditions and for applications that require relatively maintenance-free structures. The basic design consists of a triangular base with two horizontal rails on each side, and uprights at the triangle vertices for various instrument configurations. The fabrication materials include 6061-T6 aluminum pipe (schedule 40 or 80), and cast aluminum connectors. The design is self-supporting, but may be guyed. Advantages of the design compared to conventional towers include easy assembly, readily available materials, easy adjustment for rugged location or terrain, transportable components by backpack, helicopter, boat, snowmobile, ATV or alternate method, and no need for concrete. Like all structures, the design is vulnerable to snow creep in deep-snow environs, but judicious site selection will mitigate this issue. We deployed these stations with minor variations in design in Alaska and Colorado, USA and on Baffin Island, Nunavut, Canada. The towers have survived relatively severe conditions in terms of cold temperature, wind, rime, and snow deposition. Locations have included subalpine, alpine, and arctic maritime environments. Regular data transmission has been achieved via satellite modem and satellite transmitter. We discuss design and installation.

1. INTRODUCTION

We have installed meteorological stations in remote locations over the last three decades. As snow researchers, avalanche forecasters, hydrologists, climatologists, glaciologists, and recreationists, we have located most of these stations in remote areas with relatively harsh weather conditions. These conditions have not been conducive to successful data collection, instrument longevity, or structural survival due to extremely cold temperatures, high winds, heavy snow loads and repeated freeze-thaw cycles. Over the length of our experience we have tried many different configurations of instrumentation, data collection and transmission, and station structure based on location, available materials, and available funds. We have had some stunning failures and some notable successes.

The motivation for this paper was to provide other users with a basic design applicable in a variety of harsh environments, both at high elevation and high latitude, without going through the sometimes arduous and painful process that we have experienced. Many of our design details can be modified to fit individual needs and applications. This paper focuses on the structure and installation, rather than instruments or program details, which are user dependent and vary greatly.

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2. DESIGN CRITERIA

There were four overarching goals in our design.

1. The structure had to allow collection of high-quality data that would meet our application needs.
2. We wanted a simple structure that would withstand the conditions typical of high-elevation and high-latitude locations.
3. The structure had to be easy to transport into remote locations by a variety of methods.
4. Due to budget constraints, harsh conditions and remote locations, we wanted to minimize the deployment time to one day or less.

The first goal meant that the structural design had to allow instrument installation that minimized interference between parameters being measured.

For example, the structure had to allow anemometers to be mounted in a position where wind speed and direction were not affected by other instruments; radiometers could not be shaded, etc. Additionally, the structure had to allow enough vertical separation between instruments to get two instrument heights for parameters such as wind speed, air temperature, and relative humidity.

The second goal required a structural design that would withstand winds in excess of 160 km/hr (100 mph) and heavy snow loads with potentially high strain rates and creep forces.

The third goal dictated that the components of the structure had to be transportable by truck, ATV, snowmobile, boat, helicopter, or backpack. This constraint meant no single component could be too long or too heavy. We limited length to about 200 cm (~6') and weight to about 30 kg (~70 lbs). Many of our installations have been carried out on projects without significant funding so we have attempted to keep costs to a minimum. Because of weight and cold installation temperatures we also wanted a tower or structure that did not require cement footers. Sand, cement, and water weigh too much for remote, high-elevation, subzero locations. Mixing, pouring, and curing cement is problematic at cold locations.

The final consideration in our design was ease and speed of deployment. The harsh conditions typical of our station locations dictate minimizing on-site installation time for safety and cost. We developed a design that could be deployed on site, from start to finish, in one day if preliminary tasks were completed before going to the field.

3. DESIGN

3.1 Structure and Dimensions

Our preferred design is a triangular structure with three vertical pipes located at the triangles vertices, and two sets of horizontal rails linking the vertical pipes (Figure 1). Instruments may be located on the vertical legs and upper cross arms and data loggers, power storage and solar panels are located on the horizontal rails, or anywhere that they do not compromise instrument measurements.

There are a number of methods for joining tubing together. Because ease and speed were critical, we chose prefabricated tubing joints. We used cast aluminum Nu-Rail* standard T connectors (Figure 2). In reality the simple U-bolt plate on the right hand side of Figure 2 costs more than half as much as a Nu-Rail, is more cumbersome to use and requires fabrication. Nu-Rails are available in a variety of standard pipe sizes.

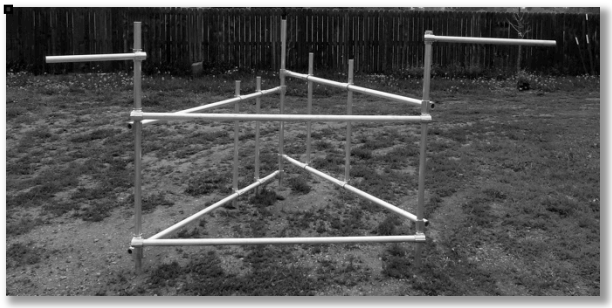


Figure 1. Tower structure with no instruments. Note the short cross arms ready for instruments and the short vertical tubes for logger enclosure, battery box, and solar panels. These tubes were smaller diameter than the main tower legs and cross arms and used the Nu-Rail in the center of Figure 2, which stepped down the diameter from 3.175 cm (1.25") to standard 2.54 cm (1") pipe.

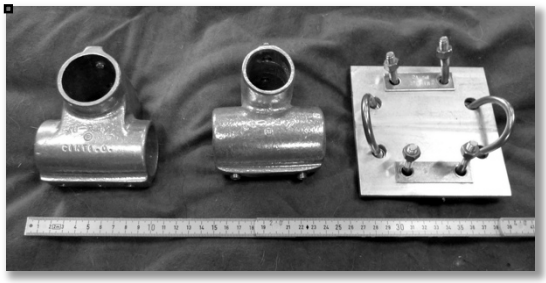


Figure 2. Nu-Rail used for major tower connections (left), reduced diameter that fit the main tower legs and cross arms on one side and a smaller diameter pipe on the other side for instruments and other tasks (center), and a standard cross plate with 6.35 mm (¼") aluminum plate drilled for four U-bolts (right).

We have used aluminum pipe for weight and longevity, and have chosen stainless steel set screws to minimize corrosion at our coastal sites.

* Brand names are for information only and do not constitute endorsement by authors or affiliations.

Both schedule 40 and schedule 80 aluminum pipe have been used depending on strength requirements for the locations. Feet were located at each vertex to keep the structure from sinking into soil and to help anchor the station to the ground (Figures 3 and 4).

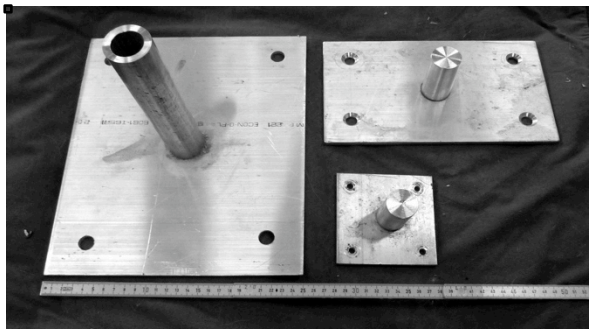


Figure 3. Different designs for the feet for vertical legs. The large plate was used in soft ground applications to keep the tower from sinking. The medium sized plate was used for rocky soil where little settling was anticipated. The small plate was used where the foot was attached directly to bedrock.



Figure 4. Feet were attached to the legs by drilling a single 6.35 mm (¼") hole through the leg and the foot stem. This was done in the field to fine tune leveling.

This tower design may be implemented in any size configuration that the user deems necessary. In practice, we have used cross bar dimensions of 180-215 (~6-7'), with vertical leg heights from 180-365 cm (~6-12'). These dimensions have been dictated mostly by the need to keep all structural materials relatively small for remote transport. We have transported the towers by backpack, snowmobile, sled, ATV, freight canoe, and helicopter. We have also shipped towers, all attachments, and the instruments 4000 km from Colorado to Baffin in northeastern Canada.

Vertical legs typically need to at least 300 cm long to elevate anemometers above the ground or snowpack, and above the rest of the instruments and structure that would otherwise affect measurements. Legs can be cut into two pieces for transport. Two 150 cm pieces can be coupled to get one 300 cm leg. Coupling can be made by an oversized collar, or better yet, by a slightly undersized plug. Both options can be held in place by bolts drilled through above and below the joint and tightened accordingly. The connector should be at least 7 cm on either side of the joint for strength and stability. The joint needs to be tight fitting to reduce instrument vibration and movement in windy conditions.

3.2 Wire Routing

Wiring from instruments to data loggers is often the weak point in a remote data collection system. We have had animal problems that have included a variety of varmints from mice to marmots, and large animal issues from elk to polar bears. We routed wiring through the structural tubing wherever possible. Flexible metal conduit was effective in rescuing wiring from chewing animals where it was otherwise exposed (Figure 5). Aluminum is light and relatively inexpensive. It is also easy to cut to necessary length. Use end connectors with flexible conduit to protect wires from sharp edges and chafing.

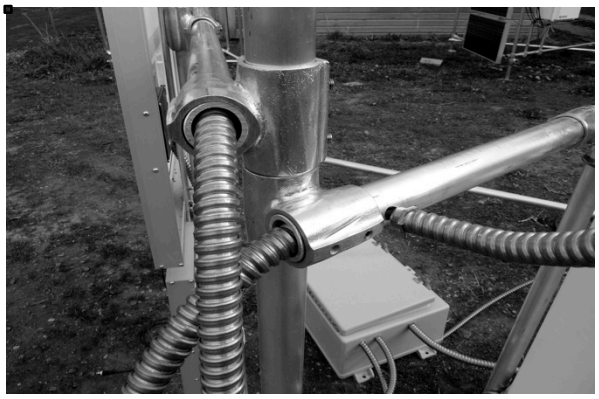


Figure 5. Flexible conduit protects wires between the structural tubes and data logger enclosure.

3.3 Guy Wires

Guying is an effective way to anchor a station in high-wind environments. Aircraft cable of 4.7-6.35 mm (3/16" to 1/4") diameter is adequate for most

applications. A loop (doubling the strength) with a turnbuckle to close the loop, or two loops with a turnbuckle in between, allows for tensioning (Figure 6).

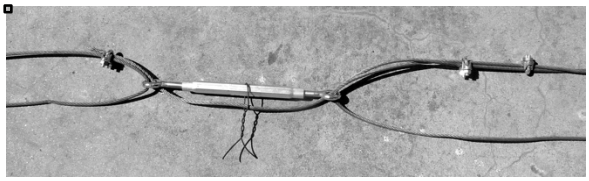


Figure 6. Guy wires shown with two loops: one goes to the ground and the other to the tower. A turnbuckle joins them. It is drilled for bailing wire that ties off to one of the loop ends to keep the turnbuckle from loosening slowly over time.

Guy wires can pose a problem when buried by snow. Creep and settlement in the snowpack can generate significant tension on the structure, causing strain, distortion and possibly failure. Keeping the guy wire short and the angle close to 45^{o} will minimize the problem.

Guy wires can be easily wrapped around the legs above the upper cross arms. No drilling or special attachments are needed. Two wraps are recommended to keep the cable from slipping and to reduce some downward load on the Nu-Rail (Figure 7).



Figure 7. A simple guy wire connection to leg above the upper cross arm. Note the double wrap around the tower leg.

Successful ground-level guy anchors can be achieved by a number of effective methods. We have drilled bedrock as described below, used existing trees, T-posts, rebar, and even dead men buried in scree.

3.4 Leg Anchors

The vertical pipes or legs were anchored at the base using the feet. We drilled several holes in each foot (Figure 3). In locations with soil, the feet were anchored with metal stakes driven at different angles to keep the legs from moving sideways or upward. In locations with boulders or bedrock, we drilled holes directly into the rock using battery powered hammer dills and used molly bolts to fix the feet directly to the rock. In northern latitudes we epoxied the anchor bolts in to keep moisture out of the drilled holes to reduce fracturing from freeze/thaw action.

3.5 Power

Solar power has been used at all of our remote locations. Wind seems like an obvious choice for some of the exposed locations, however, we have not had great experiences. We have had turbine and blade failure resulting in loss of power, and electronics failure resulting in exploded batteries. Solar has proven to be the most reliable when line power was not an option.

In high-latitude sites (above 70^{o}N) we have used two 70 Watt panels. Although lower power outputs are needed much of the year, we felt the extra generation was desirable for the shoulder season on both sides of the dark period, when days are short. Two 12 V, 100 Ah, deep cycle batteries were used at all of our locations. We have found this reserve adequate to get us through the no-light period thus far (Figures 8). Note that the solar panel leads also were routed through the battery box so that only one conduit with all power went into the data logger enclosure. The solar controller was mounted in the logger enclosure. Panels were fixed directly to the tower cross arms, or to one of the legs (Figures 9 and 13).

In scoured locations or low snow areas the panels were mounted as low as possible to reduce effects on wind and other measured parameters. In locations with complex wind, or deep snow, the panels were mounted separately on another structure with wires going to a battery box and solar controller mounted near or on the tower.

3.6 Communications

Due to cost, most of our locations have no

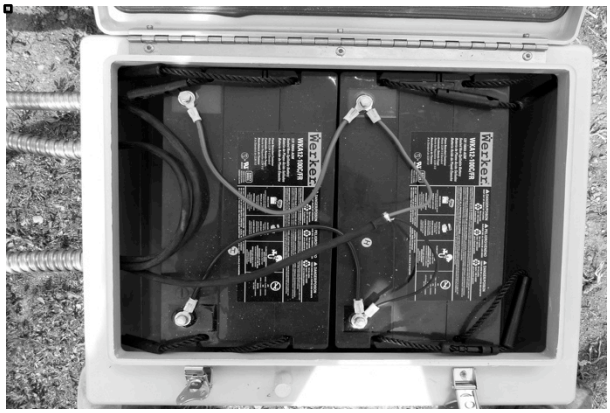


Figure 8. Battery box configuration. The two conduits at the upper left location come from the two solar panels. The lower conduit has solar and 12 V power from the batteries all going to the solar controller in logger enclosure.



Figure 9. Dual 70 W solar panels mounted on tower cross arms. We have used Nu-Rails, U-bolts and aluminum plates to mount the panels, but many different configurations can easily be used for mounting.

capabilities for data transmission and data is stored on site until manually retrieved. Regular data transmission has been achieved via satellite modem (NAL Research/Iridium for the Alaska site), and satellite transmitter (CSI/ARGOS/NOAA for the Baffin sites). Near real-time data from these sites can be viewed at:

Alaska –
http://avalanche.state.co.us/obs_stns/alaska/index.php
Baffin –
http://www/clyderiverweather.org

4. BEFORE GOING TO THE FIELD

4.1 Shop Work

Preparation before going to the field was essential to successful and short deployment time. We used a paint pen to label all parts as we disassembled the station to make reassembly in the field faster and more efficient. Parts that did not have a writable surface, such as wires, were labeled with marked tape.

We beveled all sharp edges on tubes and plates to minimize wire chafing and cuts to fingers and hands when installing. Rat-tail files worked well for tube interiors and a large-toothed flat file worked well for outside diameters. Half-round wood rasps performed both tasks even more effectively. We pre-drilled holes that could be drilled before deployment, such as stake holes in feet (Figures 3 and 4). We drilled many holes (4-8) so that we had options in the field. We assembled a small supply of extra nuts, bolts, set screws and all small parts that might have been lost during assembly in the field. We assembled a tool kit hat matched the tools used for the trial set up and take down, as well as tools that might have been needed in the field for site preparation.

4.2 Testing

If the final location is truly remote and expense is a serious issue (e.g. helicopter time), then it is worth assembling and testing the entire meteorological tower before taking it to the field. It is especially important to test communications, particularly if they are satellite based. Radio communications should be tested too, but there will also likely be local line-of-sight issues at the final location. If satellite methods are being used, it is critical to check coverage and repeat times for orbital satellites, and coverage in general for orbital or fixed satellites at the final location.

5. INSTALLATION

5.1 Site Preparation

Remove all vegetation and debris that will make installation difficult or compromise measurements. Remote locations seldom have perfectly level sites for installations. Leveling is important for parameters like radiation, but also for wind speed

and direction. It is difficult to level the entire triangular tower assembly once it is fully constructed, but not too difficult to make minor adjustments.

5.2 Tower Erection

Lay out the three pairs of lower cross arms at the location you choose with one leg at each vertex (Figure 10). Slide all Nu-Rail connectors on each leg, and any other connectors that you need for the data logger or battery box on the horizontal rails. Place the feet on the legs. Fix one Nu-Rail near the foot of the first vertical leg and fix one lower cross arm into the same Nu-Rail. Fix the other end of the cross arm to the Nu-Rail on the second leg. Stand the second leg up and slide the Nu-Rail up until the cross arm is horizontal. A 30 cm (12") pocket level works well for this application. Tighten the Nu-Rail to fix the second vertical leg in this position. Fix the second lower cross arm in the second vertical leg's Nu-Rail and to the third leg at the other end of the cross arm as above. Check for level and adjust. Fix the third horizontal leg in between the third and first legs and level.

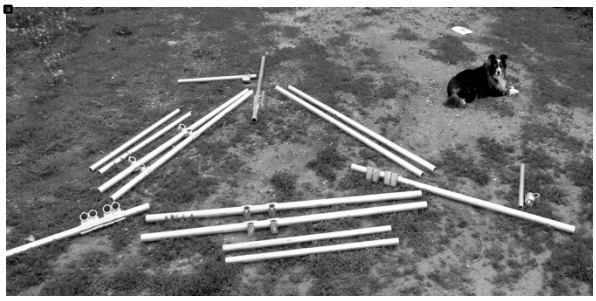


Figure 10. Tower layout out before erection. All Nu-Rails are on their final tubes, but not fixed in final locations. In a real field setting there would be some ground preparation at each vertex point where a foot and a leg would be located.

You should now have three legs connected by three horizontal cross arms. The cross arms should be nearly horizontal, but you should check and adjust all. Also check the legs for vertical. Only minor adjustments should be needed at this point. Repeat the procedure for the three upper horizontal rails and again check for trueness in the horizontal and vertical. This process can be completed by one person, but is considerably faster with two or more.

Stake the feet in place, if mounted on soil surface. Drill and bolt, if installing on boulders or bedrock. If guy wires are being used, install all three sets, then incrementally tension all three vertices. Rotating around the tower and tensioning gradually will minimize distortion. After tensioning and staking is finished, check the tower again for vertical. At this point it is the vertical legs that matter and the horizontal cross arms can be compromised to keep the three legs vertical.

Before leaving the site check all clamps and U-bolts for tightness and take one more twist on all Nu-Rail set screws.

5.3 Ties and Clamps

UV-resistant, plastic zip ties are effective over a few years, but need regular replacement. We have found that they are particularly useful for set up and installation, but steel hose clamps are preferable for the long term (Figure 11). For the small amount of extra expense, they are well worth the cost. Clamps near the ends of all otherwise free runs of wires and every 30-50 cm in between are recommended. Wires are run through the structural tubes for added protection in any location where it makes sense on the way to the logger.



Figure 11. Daniel Bowker tightens hose clamps above and below a cross arm to secure flexible conduit. Wires were combined in all possible runs to reduce the number of individual conduits and connectors, as well as the number of ports into logger and battery boxes.

6. APPLICATIONS

Examples of some of the station deployments are provided below. Figures 12-14 show the three towers on Baffin Island, Canada. Figures 15 and 16 show the Alaskan Mount Tiekle tower location near Thompson Pass, east of Valdez. Figures 17 and 18 show towers at the Fraser Experimental Forest, near Fraser, Colorado.



Figure 12. Ilkoo Angutikjuak examines the Akuliaqattak Station (70°18'50"N, 68°9'24"W) in near whiteout conditions. Note temperature/relative humidity sensor on center leg, which has been bent by a visiting polar bear. Two such bear incidents have fortunately not compromised measurements.



Figure 13. Esa Qillaq and Henry Huntington service the Ailaktalik.



Figure 14. Glen Liston, Henry Huntington and Esa Qillaq make minor adjustments to the Silasiutitalik Station.



Figure 15. Alaska Rendezvous Guides crew completing site preparation for tower high on the shoulder of Mount Tiekle in the Chugach Range.



Figure 16. Nick Houfek points to the anemometer after a heavy snowfall season in the Chugach. The leg will be extended vertically to accommodate extreme snow depths.



Figure 17. Daniel Bowker hangs the lower anemometer while Roger Tyler and AJ Marsh wire instruments and data loggers at a wetland location at the Fraser Experimental Forest.



Figure 18. Forest meteorology application at the Fraser Experimental Forest.

7. SUMMARY

This meteorological tower design provides a proven, flexible starting point to meet almost any remote application where severe conditions are probable. Cost is greater than a simple Rohn 25G (Elder et al., 2009) or the equivalent, but flexibility, transport, stand-alone design, and other advantages make this design attractive.

8. ACKNOWLEDGMENTS

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