Submillimeter Array Technical Memorandum

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Summary of the Testing Done to Size the SMA Antenna Foundations

Introduction:

The load bearing parameters of the volcanic soil at the location of the SMA on Mauna Kea are at the lowest end of the range for normal soil materials. In this range there is considerable uncertainty on the dynamic stiffness that should be used in modeling the foundations. A conservative approach to the pad design results in foundations that are extremely large and consequently very costly. It is imperative, therefore, that we obtain confirmation of the actual stiffness of the foundations so that they may be properly and most economically sized.

The construction contract on Mauna Kea was written to permit testing of a single test foundation in a characteristic soil prior to the final choice of sizes for the others. The test which was envisioned was the attachment of a load, designed to rotate the foundation much in the manner of a wind. Since the foundations are stiff enough that the main strains are accommodated with a solid body rotation, especially in weak soils, the stability can be measured with, electronic levels at the top of the structure and the results compared with models for the antennas.

The Requirements:

Much of the fundamental design of the SMA is dictated by the fact that there is no protection of the antenna from wind loads. The low opacity conditions on Mauna Kea were found by Masson to be poorly correlated with wind, thus requiring that significant wind loads be accommodated. It was decided that in order to insure that a large percentage of the environmental conditions fell within acceptable operating specifications, that the antennas would need to work to full specification in a 14 m/sec wind. A wind of 14 meters per second is thought to be representative of a 96th percentile wind and thus represents about 96% of the good operating conditions.

The load presented by a 14 m/sec wind and its effect on the antenna, varies greatly with the azimuth angle and elevation. So too does the effect of that wind on the phase of the interferometer and the pointing. The design study of 1992 outlines a large number of error budgets under various conditions which contribute to various aspects of the design. In general, we attempted to distribute the error budget economically between the antenna structure and the concrete foundations.

The worse case load, from the standpoint of the foundation, is the maximum torque condition caused by a head-on wind at the lowest working elevation of 30 degrees. The calculation of the drag of the antenna, using a predicted drag coefficients from outside tests on similar structures, predicts a torque (an overturning moment) under these conditions of about 15,100 foot pounds. **All** higher elevations produce a lower torque. Cross winds produce a smaller effect on the actual phase and pointing, being at an angle to the line of site.

The model for the antenna allows the intersection of the axes to move a total of 23 microns under the presence of the head-on 14m/sec wind. Note that this is a total motion of 23 microns, not a variation of 7.3 microns. We have no way to predict what the variation in parameters will be over the integration time of the interferometer, but we certainly know that the RMS error in the phase will be significantly less than the peak to peak variation. This is likely to be an even more conservative view on Mauna Kea than elsewhere, since the power at higher wind frequencies was measured by Cheimets and found to drop off very quickly in MM Valley.

The error budget for the mount deflections was done using finite element modeling of the entire antenna structure. While the finite element analysis is very complex, there is a relatively easy intuitive approximation. Table 1 one shows a rough approximation of the distribution of tilt among the various components and how this tilt would be reflected in motions of the axis. The budget gives about half the phase error to the foundations and the rest to the mount. As you can see, foundation stability is critical to maintaining phase, even though it is but a small factor if you consider only the pointing error.

Table 1: Distribution of Antenna Mount Errors

Component	Deflection	Characteristic Dist. to Axis	Implied Motion at Axis
Foundation	0.4 arc sec	5.9m	12 microns
Base	0.1	4.0	2 "
Bearing	0.35	3.0	5 "
Alidade	0.35	1.5	3 "
Total	1.2 arc sec		22 microns

The Problem:

Soon after the start of the Mauna Kea design, soil tests were done at the surface of the site by our geotechnical contractor Harding Lawson (HL). It was immediately evident that the results Gould be highly controversial. HL concluded that the soil at the site could be as poor in load bearing capacity as 1/3 that of the Subaru site at the summit and as much as 15 times worse than the soil at the Haystack site. Geotechnical contractors are typically held accountable if the load bearing is less than prediction, thus no amount of discussion would cause them to refine their data to a "most likely" figure rather than a "better than" estimate. When coupled with our instructions to our architect to insure that no foundation tilt was worse than 0.4 arc seconds for the described load, the result was a very large, and obviously very expensive, initial design.

Since the ability of a foundation to resist the overturning moment varies approximately by the cube of the width and the concrete costs similarly, it was apparent very quickly that we had a very high interest in refining the size of the foundations from a worse case design to a most probable design. The savings in cost over 21 foundations was such that even the correction of two or three foundations after their completion would still produce a net cost savings. We were, furthermore, convinced that the soil at the depth of the base of the pad would, on the average, be better than sampled by HL. Normally, this could be uncovered by seismic data at the site, where the modulus of the soil can be directly calculated from the sound velocities. This is not possible at the SMA site because the variation in soil parameters, even across a single pad, are often very large, thwarting any logical seismic conclusions. Many drill holes could have uncovered the correct character of the subsoil, but the cost of multiple drill holes at 2 1 sites would have greatly cut into any savings in concrete.

Knowing these constraints, and the high cost of concrete at the summit, we permitted the architects to complete a worst case design for the foundations at the summit. However, the construction contract was configured so that we had a week to test the foundations before a new size was adopted for all 21 foundations. Most of the following work was done to develop enough robustness in our own knowledge to reliably make that decision immediately upon seeing the test data.

Static Load Testing at Haystack:

No attempt was made to make the test foundations at Haystack fully meet specification. They did, however, provide a good base from which to extrapolate. A test loading of test foundation #1 at Haystack Observatory was done in the fall of 1994 to determine the approximate stiffness of the prototype foundation. A moment was placed on the foundation by lifting a load of 1050 pounds with the top of an 0.5 meter vertical bar. (see Figure 1) The result of several tries indicated that the rotation of the foundation was -0.35 arc sec, which was roughly that amount predicted by the Leo A Daly structural designer using estimated characteristics for the Haystack soil. Since this moment is only about half the moment from a head-on, 14 m/sec wind with the reflector at 30 degrees elevation, we concluded that this foundation was weaker than we needed on Mauna Kea, but close enough to prediction that we retained at least some faith in the structural models.

Load Testing With an Antenna Mount:

The purpose of testing the Haystack foundation with an actual antenna mount was three fold:

1) to verify that the previous static load test is a valid measure by determining the actual rotation of an antenna and its foundation with the correct moment applied;

2) to measure the stiffness of a well documented mount to determine if the stiffness of the mount when coupled to a foundation was agreed with the model;

3) to check the interface between the mount and the foundation.

Both results were needed prior to the start of the foundation construction on Mauna Kea to insure that the installed foundations would be substantially correct.

Antenna mount #1 was equipped with 5 electronic levels in preparation for working out the pointing budget for the instrument (see Figure 2). These levels were augmented with two additional levels which could be placed in positions 6 -10. The mount was then placed on the foundation prototype at Westford, generally referred to as pad #1.

In order to be sure that the measurement noise would not swamp these small readings, we chose to apply forces some 2 x to 3 x the actual wind load for the foundation test. The correct load at the elevation axis to reproduce the wind was 780 pounds. Using the fork truck and a strain gauge we applied loads ranging from 1160 pounds to 2060 pounds. This produced tilts which were of several arc seconds in the total structure, all of which were then normalized to the correct wind by dividing the result by the pull load over 780 pounds. A number of pull tests were conducted in both the directions of the elevation axis as well as normal to it. The first set of data is shown below in Table 2.

Table 2: The first sequence of tilt data from Mount #1

Load (pounds)	Average of levels 1,3, 5 normalized to a 14 m/sec wind	Average of Levels 6&7 normalizedtoa 14 m/sec wind
1160	2.3 arc sec	0.56 arc sec
1500	2.4 arc sec	0.49 arc sec
1270	2.5 arc sec	0.39 arc sec
1740	2.5 arc sec	0.61 arc sec
~~2060~~	~~3.4 arc sec~~	~~9.79 arc sec~~
Average	2.4 arc sec	0.59 arc sec

The tests with the mount in place on foundation #1 indicated tilts much higher than we expected. The average of five tests in the direction perpendicular to the elevation axis was 2.4 arc seconds. This compares with a model prediction of only 1.3 arc seconds (Table 1). At the same time, the foundation itself, as measured at position 7, averaged 0.59 arc seconds at the normalized wind load, in reasonable agreement with the earlier data.

It was soon discovered that the extra tilt in the mount was coming from the azimuthal bearing. We confirmed this with dial gauges between the top and bottom portions of the mount. Subsequent tests with the second mount on the same afternoon indicated essentially of the same character. Although the data were not as complete, they agreed with the character of the flexures in the first mount. This problem was later traced to a lack of preload in the bearings. The results of the bearing rework will be reported in a later Technical Memorandum..

The tests with the mount confirmed that the antenna-foundation interface would work as designed and that the tilts of the foundation were predictable by our simple solid-body model of the foundation rotation. We decided that we could safely proceed'as planned with the Mauna Kea tests and adjust the size of the foundations accordingly.

Mauna Kea Test on Foundation Number 12:

The initial foundation at Mauna Kea was going to involve a test on foundation # 9; however, we chose to switch to foundation #12 to be further from the road to Puu Puliahu. Foundation #12 was in quite soft soil and was thought to provide a good test of the design. Since we expect primarily solid body rotation from the foundations, both from the Haystack measurements as well as the design, we chose to apply a rotational moment to the foundation by placing a 4150-pound cement block on the second step (see Figure 3). The block, at a radius of 9.75 feet, provided a rotational moment over 2.6 times that of the antenna in the 14m/sec wind. Before the test was made, it had been observed that the soil at the depth of the base of the foundation was indeed similar to the soil at the Subaru site, and thus probably of a much higher modulus than had been used in the calculations, Thus, we had some expectation that only a little rotation would be observed. We also had the additional benefit of having about 60% of the other foundations excavated at the time of the test, so that we were sure that foundation number 12 was at the lower end of the soil bearing parameters and not the upper end.

The electronic levels that are used by the SMA are, in effect, bubbles of air that float in a resistive medium. An accurate bridge circuit reads out the position of the bubble and can sense tilt with a precision better than 0.2 arc seconds. The practical limitation on sensitivity is set by your ability to give the level a good stable thermal environment, since the readings wander from even the slightest air current.

Prior to making the test at Mauna Kea, two electronic levels were mounted on steel plates about 12 cm square to increase their thermal time constant. Leveling screws were mounted on the plates to permit the levels to be brought within scale on the concrete. A battery operated readout box is provided by the manufacturer and would serve as the main readout mechanism. We also brought a computer with A-D card to the summit to record the readings and a video camera to record the entire episode. The test was scheduled for the morning of Sept. 5, which was the first working day when the foundation had sufficient cure time.

Immediately upon opening the shipping container in Hilo it was apparent that the readout electronics not operating correctly. After several hectic hours the cause of the malfunction was not yet know, but it was determined that one of the channels was still operating at about 0.4 arc seconds resolution. (It was later determined that this malfunction was probably caused by a shorted thermistor which damaged some of the readout electronics.) After recalibrating several times, it was decided to make the load test with the one channel. (The calibration of the level was also done after the test with the same result to an accuracy of perhaps 20%.)

The load test did not immediately show any motions of the foundation with the placement of the 4000 pound block to at least an accuracy of 0.4 arc seconds. After reviewing the video tape of the test it was possible to see one or two bit transient when the block was put down too hard and also a large deviation when the driver accidentally drove onto the apron of the pad. Otherwise, the motions were not detectable. This put a lower limit on the pad stability at least 2.6 times better than the conservative soil model and probably better. Not surprisingly, the required soil parameters would be about equal to those realized at the Subaru site at the summit. Since the variation of soil parameters is very high over the SMA site and we had only an upper limit, we decided to choose a size for the foundation which would work with the Subaru-like soil and no better. As an additionai measure of conservative thought, we sized me pads for the smallest chord, although the characteristic size of the hexagon base is somewhat larger, particularly with the stability rising as to the cube of the chord. We did not get any help from the computer record of the event, since the decreased sensitivity of the level and the settings of the A-D did not produce a useful set of data.

The fmal discussions regarding the Mauna Kea foundations involved finding a new geometry that Kiewit Pacific would build economically. The most efficient designs are not always the easiest to construct. We also needed a geometry for the foundation that was very stiff, since all the structural models assumed but a small flexure in the concrete. Kiewit was very helpful in suggesting a sloped geometry that saved an average of 45 cubic yards of concrete per foundation over the original design. Figure 4 compares the 3 foundation geometries.

Post Construction Testing

The pressures of the construction schedule, the repair of the electronic level readouts and the desire to let the pads cure to the correct hardness, only permitted the testing of two of the foundations during the construction process. The 4150 pound block used previously is still the easiest way to apply the rotational moment to the foundation; however, the only location at which to place the block in the current design is on the rim of the foundation, since it would slide off the sloped surface if placed further out. The use of the block in this manner applies approximately that same rotational moment as predicted by the 14 m/sec wind.

On October 25th the cement block was placed on the rim of foundations 21 and 15 with the both channels of the electronic level operating at the full 0.2 arc sec resolution. Foundations 21 and 15 were chosen because they were believed to be two of the four that were in the worst soil conditions (foundations 17 and 13 being the others). There were no detectable motions on the readout box to an accuracy of at least 2 bits and probably higher. We concluded, therefore, that the design would work as specified, although again, we had only an upper limit. A more complete set of test data was taken on December 12 and 13 and is covered in Technical Memorandum No. 9 1. The more complete data confirmed that the preliminary readings were substantially correct and that the design meets the required specifications.

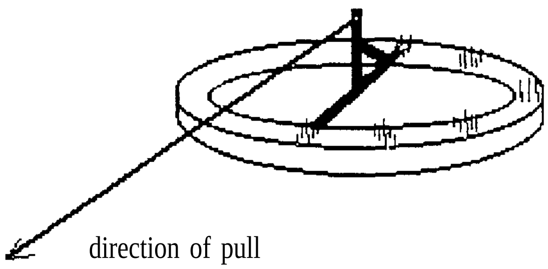


Figure 1: static load geometry for foundation test

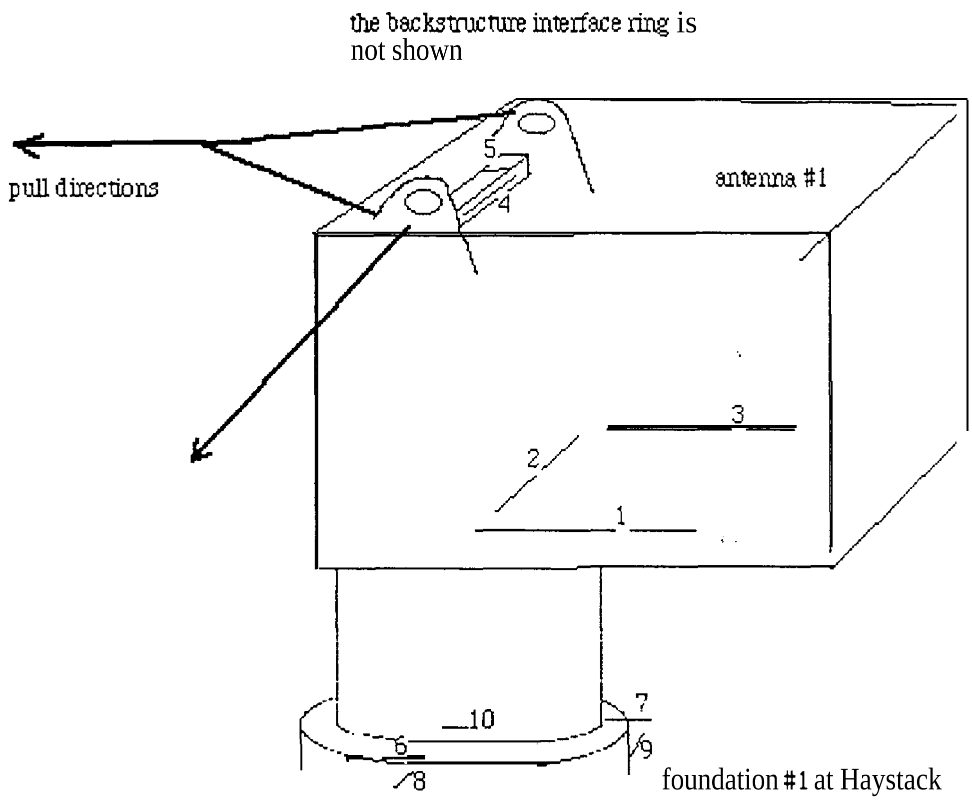


Figure 2: **Electronic Level locations during the mount and foundation testing**

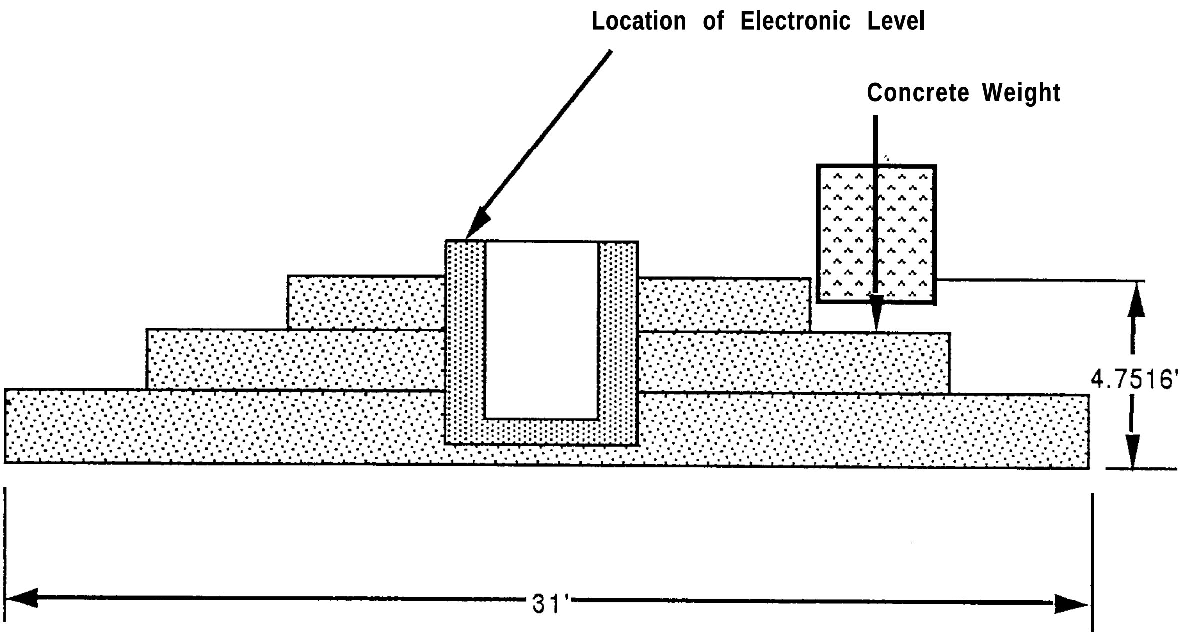
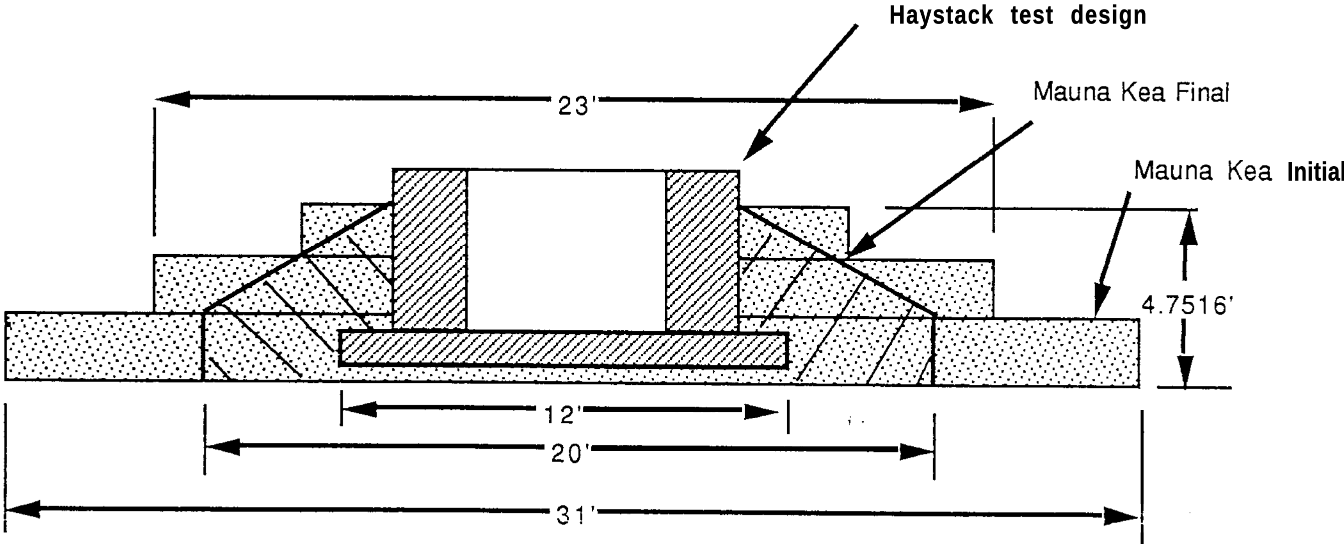


Figure 3: Test Configuration for Foundation Number 12



Note: The 31' foot base and the 20' base are hexagonal in shape. The dimension shown corresponds to the distance across the base along the smallest chord.

Figure **4:** A schematic comparison of the three foundation types.