Submillimeter Array Technical Memorandum

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From: Martin Levine

Servo-Controlled Azimuth Tension Wrap

1. INTRODUCTION

The history background of the SMA azimuth wrap development efforts is discussed in detail in Technical Memorandum Number 70, 29 June 1993. To recapitulate, the design of the SMA azimuth cable wrap is driven by the requirement to transport local oscillator reference signals in the 6 to 8 GHz frequency range to the rotating platforms with minimal phase perturbation. The reference frequencies are transmitted as modulated optical signals over single-mode fiber; the problem is to bring these fibers from a fixed point on the earth into the rotating antenna cabin while constraining the maximum change in the optical path length caused by thermal and mechanical stresses to 10 microns or less.

Measurements of the fiber path-length variations induced by mechanical stress clearly demonstrates that optical fibers are much less sensitive to pure torsional motion than to either bending or elongation. The azimuth torsion wrap design exploits this characteristic by absorbing the rotation of the platform entirely in twisting of the fiber. To this end, a vertical segment of fiber or fibers is clamped at each end and is allowed to rotate freely between the clamps. The fibers are aligned as precisely as possible along the axis of rotation, and the fiber clamping mechanisms are positioned on the vertical section of the fiber such that there no bends within the rotating fiber segment.

2. DEVELOPMENT HISTORY

A key observation, early in the development phase of the azimuth torsion wrap, was that there is a direct relationship between the axial tension applied to a transmitting fiber and the measured phase shift through the fiber. Further, the effects of rotation of the fiber appear to be manifested, to first order, as variations in fiber tension which translate directly to phase error. The example of Figure 1 shows tension and phase shift plotted against the same time base; the total rotation angle is 540 degrees and the rotation rate is about 1.5 degrees/second. The similarity of the tension and phase signatures is evident, but this alone does not establish a causal relationship. A preliminary and somewhat primitive experiment, in which the measured tension was manually maintained at a constant value as the fiber rotated, provided sufficient confidence in the existence of a cause-and-effect mechanism to justify the next phase of the development.

A simple measurement fixture was then constructed, consisting of a three-axis optical stage for the alignment of the fixed end of the fiber loop and a servomotor to rotate the (simulated) moving platform. Fiber tension was measured by clamping the two fibers in the loop to the movable arm of a small strain-gauge load cell. The body of the load cell, in turn, was secured to the optical stage. In the final development phase, the optical stage axial micrometer was replaced by a second servomotor. The tension loop was then closed through a PMAC motor controller using the load cell as the tension sensor.

3. SERVO-CONTROLLED TENSION WRAP DESIGN

3.1 Prototype Azimuth Wrap

A prototype of the servo-controlled azimuth wrap was set up in the laboratory as shown in the sketch of Figure 2. The optical fiber under test is formed into a continuous loop such that two closely-coupled strands are subjected to essentially the same thermal and mechanical environment . The closed end of the loop is clamped into a mandrel which is rotated by a small servomotor. A ten-turn precision potentiometer mounted on the motor shaft serves as the rotary position sensor for the PMAC-based motor controller. At the open end of the loop, the two strands of fiber are clamped into a v-groove adapter which is fastened to the actuator arm of a Minibeam MB-5 strain-gauge load cell. The Minibeam load cell is ideally suited for this application; since the strain gauge simply measures the deflection of a six mm thick aluminum block there are no moving parts and very little displacement of the actuator is required.

The load cell is rigidly fastened to the moving platform of the Newport M-462 three-axis optical stage and moves with the platform. The platform in turn is driven by a Newport motorized micrometer with an integral optical incremental encoder. The outputs of the strain-gauge monitor and the optical encoder are fed to a second channel of the PMAC motor controller to close the tension servo loop. A listing of Bob Calder's commented PMAC code for the tension servo is included for reference as Appendix A to this memorandum.

3.2 Test Instrumentation

Since the fiber transmission path must be returned to the stationary reference frame for measurement purposes, the total path includes two rotating segments. It is assumed for the purposes of this evaluation that the mechanical phase is approximately double the one-way phase variation. The fiber segment under test was inserted into one leg of the otherwise symmetric optical system, as shown in the simplified block diagram of Figure 3. The SMA Master Reference source, set to 6.682 GHz, was used to modulate an Ortel 3515A laser transmitter. The modulated optical signal was split by an Aster power divider and routed directly to one optical diode receiver. The other output of the power divider is routed through the azimuth wrap mechanism and the fiber under test. Each optical receiver output is followed by an associated Reference Signal Generator: the phase record is produced by feeding the outputs of the Reference Signal Generator to the HP 8720 Vector Network Analyzer. The test data includes ambient temperature effects on both the fiber under test and the electrical/optical components; however, in most cases the time scales of the temperature and rotational perturbations are quite different and it is relatively straightforward to distinguish the effects.

4. MEASURED PHASE STABILITY PERFORMANCE

Figure 4 extends the time-line of Figure 1 to demonstrate the effectiveness of the fiber tension servo system; the servo loop was closed at approximately 140 minutes into the test run. The peak-to-peak phase excursion as the fiber loop rotates through 540 degrees is reduced from about 0.2 to 0.3 degrees at 6.68GHz to about 0.05 to 0.1 degrees. All phase measurements are quoted for two transits of the rotating fiber segment; the phase error for one fiber is assumed to be one-half this value. This average improvement factor of approximately three appears to be typical of the performance capability of the tension-controlled wrap. It should be noted that there are residual mechanisms which do not respond linearly to the reduction in tension variation; the decrease in peak-to-peak tension change under closed loop conditions is much greater than the corresponding decrease in peak- to-peak phase excursions. Also, the test instrumentation is a simulation of a complete reference distribution system, including a laser transmitter, two optical receivers, 100 meters of Sumitomo Temperature-Compensated Fiber, and associated synthesizers and phaselock loops. Under these circumstances, the phase fluctuations attributable to ambient temperature changes are larger than the observed rotational effects.

Another view of the performance of the servo-controlled tension wrap over a period of 17 hours is shown in Figure 5 . The slow phase variations, which are superimposed on the 0.05 to 0.1 (two-fiber) rotational effects, appear to be temperature related. The worst case peak-to-peak phase variation over this full period, including temperature, drift and rotational contributions, is less than 0.6 degrees at 6.68GHz. The stability of the measured tension throughout the 17 hour run is remarkable; less than 0.01 pounds peak-to-peak with no detectable aging or temperature effects.

The servo controller provides an elegant method of determining the optimum system settings for average tension. Figure 6 shows the results of an automated scan of tension values between 0.3 and 0.9 pounds (distributed over two fibers). The tension was maintained at a constant value for 1.5 hours while the fiber was continuously driven through 540 degree rotation cycles. The data shows that the tension setting does not appear to be critical, but best overall stability and repeatability is obtained in the range 0.5 to 0.7 pounds. It is also evident that, at least for the relatively large excursions encountered in this experiment, the phase excursion coefficient is approximately 5 degrees per pound. This relationship is reasonably consistent with the data of Figure 5, which shows a coefficient of between 5 and 10 degrees per pound for very small tension fluctuations.

Another way of looking at the measured data is to plot tension and phase as a function of rotation angle, as shown for both the open and loop cases in Figure 7. The upper plot shows tension as a function of rotation for ±270 degrees of rotation from the nominal neutral point. The open-loop curve illustrates a phenomena which was observed in the past, but with not nearly the clarity: the rate-of-change of tension with respect to rotation angle increases sharply as the angle moves away from the zero reference position. Unexpectedly, the slope deceases again at the extreme ends of the rotary motion. The measured open-loop phase excursion, plotted in the lower graph, precisely mirrors the tension variations, even to the flattening at the extremities. These observations offer a plausible explanation for some cases of nonrepeatable or inconsistent open-loop data; the measured results are dependent on the selection of the reference position and the optimum choice is not always obvious before the data is taken.

The closed-loop data of Figure 7 offers some interesting features as well. The tension plot shows a persistent "eye" at the extreme negative rotation angle . The origin of the eye is clearly a tracking error in the tension feedback loop and must be addressed as a servo design problem. It is not clear why a similar eye does not appear at the positive extreme.

5. CONCLUSIONS AND RECOMMENDATIONS

The azimuth torsion wrap concept initially described in SMA Technical Memorandum 70 appears to be a viable approach to the problem of transmitting signals to and from the rotating antenna platform. The addition of the tension servo greatly simplifies the installation and maintenance of the azimuth wrap, and permits continuous remote monitoring of the status of the system. A detailed review of the open-loop data presented in Technical Memorandum 70 shows that under very carefully controlled conditions it is possible to obtain phase error performance at the same level as the closed-loop approach. However, a high level of skill and expertise is required in the open-loop situation; the closed-loop installation procedures are much less critical and appear to maintain good performance over much longer intervals. Furthermore, the tension servo tends to restore the system to its original state even after major mechanical perturbations to the rotating fiber segment.

There are some problem areas which have not been fully addressed. Since the fiber under tension acts like a vibrating string, the mechanical design must be carefully implemented to minimize excitation of the fiber resonances. Damping mechanisms, such as viscous gels or liquids, are also useful if they can be incorporated without compromising the phase error performance. Also, mechanical durability of the torsion wrap has not been fully demonstrated. The laboratory prototype has been operating continuously for 360 hours as of the date of this paper. We propose to continue the mechanical life test for as long a duration as feasible and to periodically evaluate phase error performance and to estimate degradation, if any is evident.

There are still open questions as to whether the tests run to date accurately reflect the usable performance of the torsion wrap. Since all phase measurements are performed in the fixed reference frame, it is possible to postulate that the phase excursion in one direction of transmission is exactly compensated by an equal and opposite phase change in the opposite direction of transmission. It is difficult to construct a credible mechanism to perform this feat and, in fact, the demonstrated dependence of the phase on the measured tension implies that the phase error introduced by each fiber in the rotating segment must have the same sign. Furthermore, all phase-correction feedback systems are subject to the same objection if the feedback signal is transmitted over a separate fiber. It is difficult to design a definitive experiment to resolve this issue, but a refinement of the procedure described above in the planning stage. The return fiber in the rotating segment will be replaced by a partially-reflecting mirror at the present location of the fiber loop. The phase and amplitude of the reflected signal will be sampled by an (optical) directional coupler and the phase compared to the transmitted phase by means of the vector network analyzer. Of course this experiment is still not sufficient to prove our hypothesis, but it does use the same optical path for both directions of transmission.

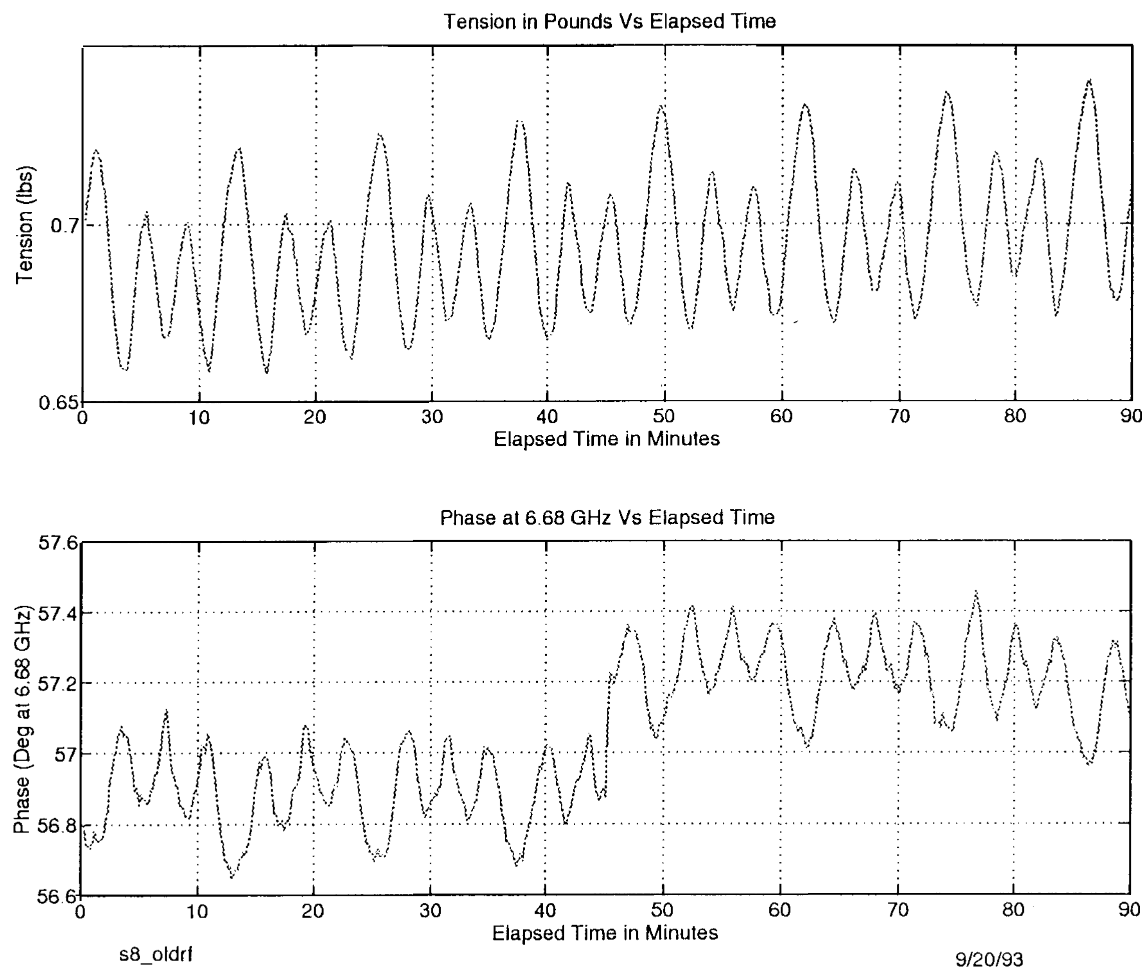


Figure 1 FIBER TENSION AND PHASE ERROR VS ELAPSED TIME

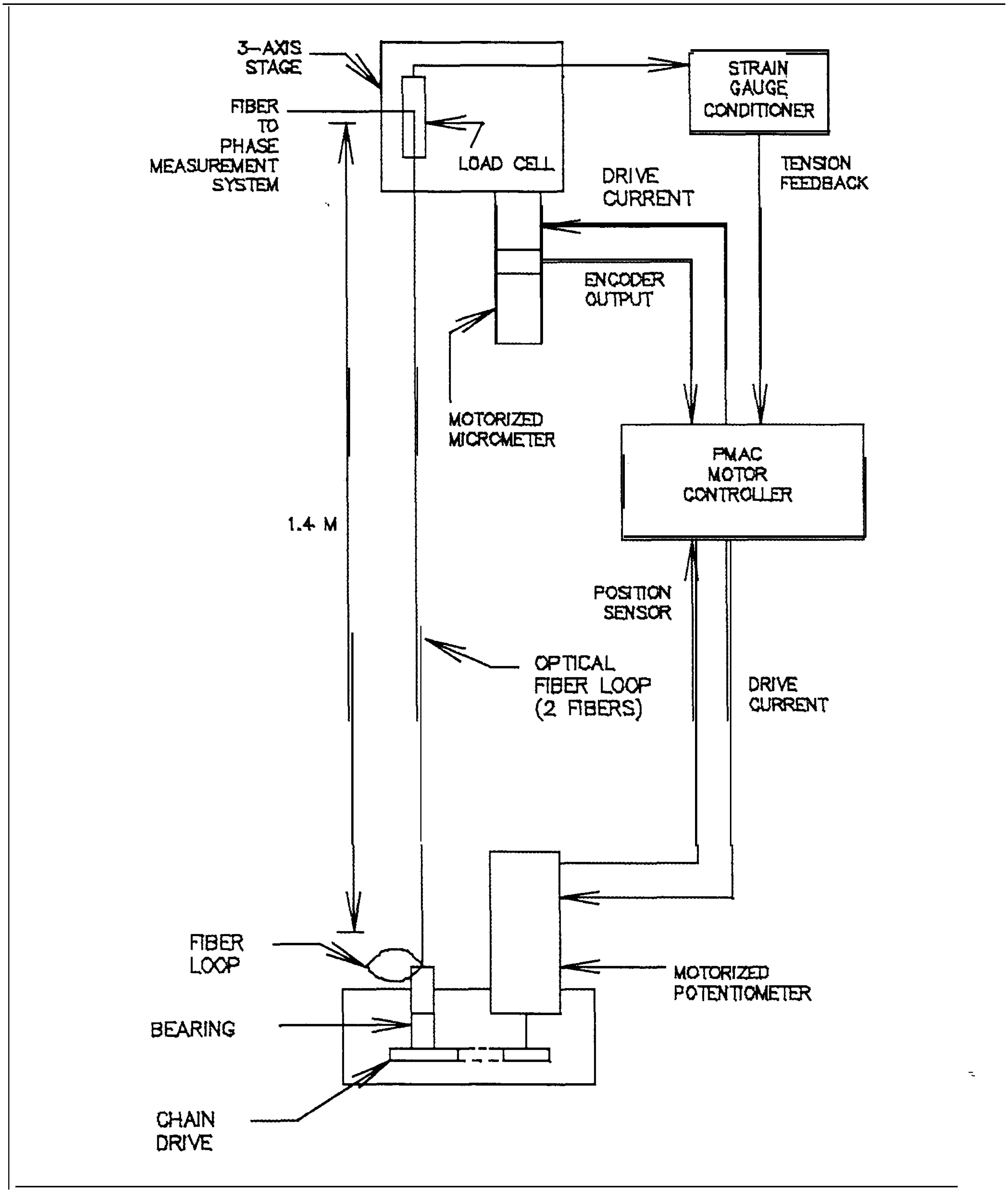


Figure 2 TENSION SERVO TORSION WRAP TEST FIXTURE

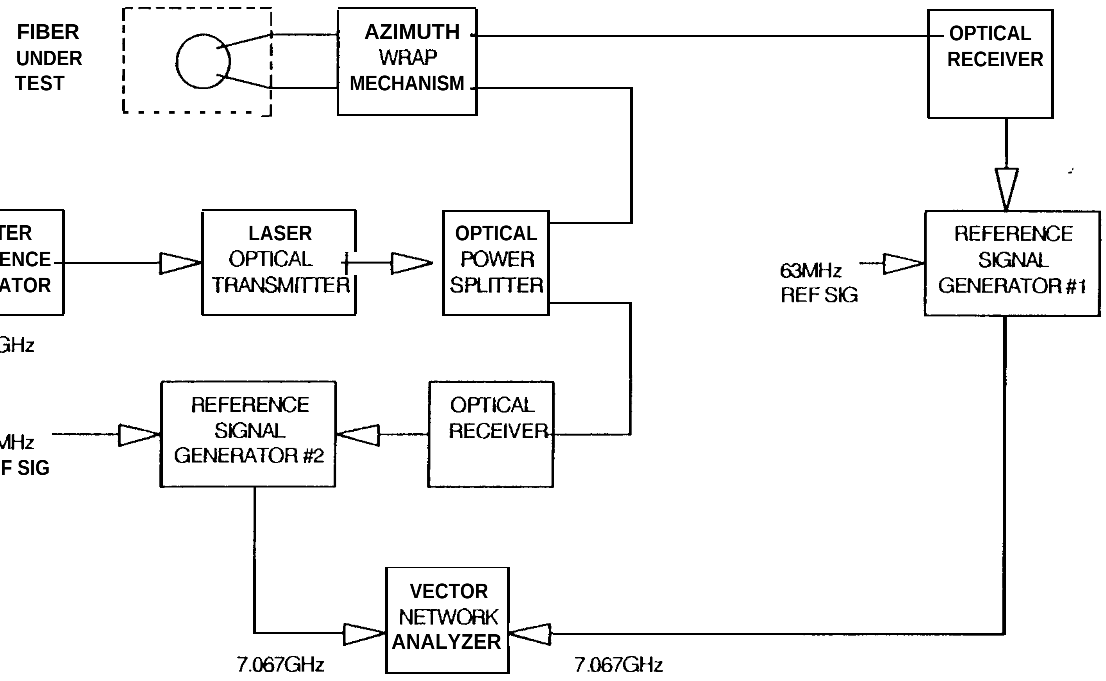
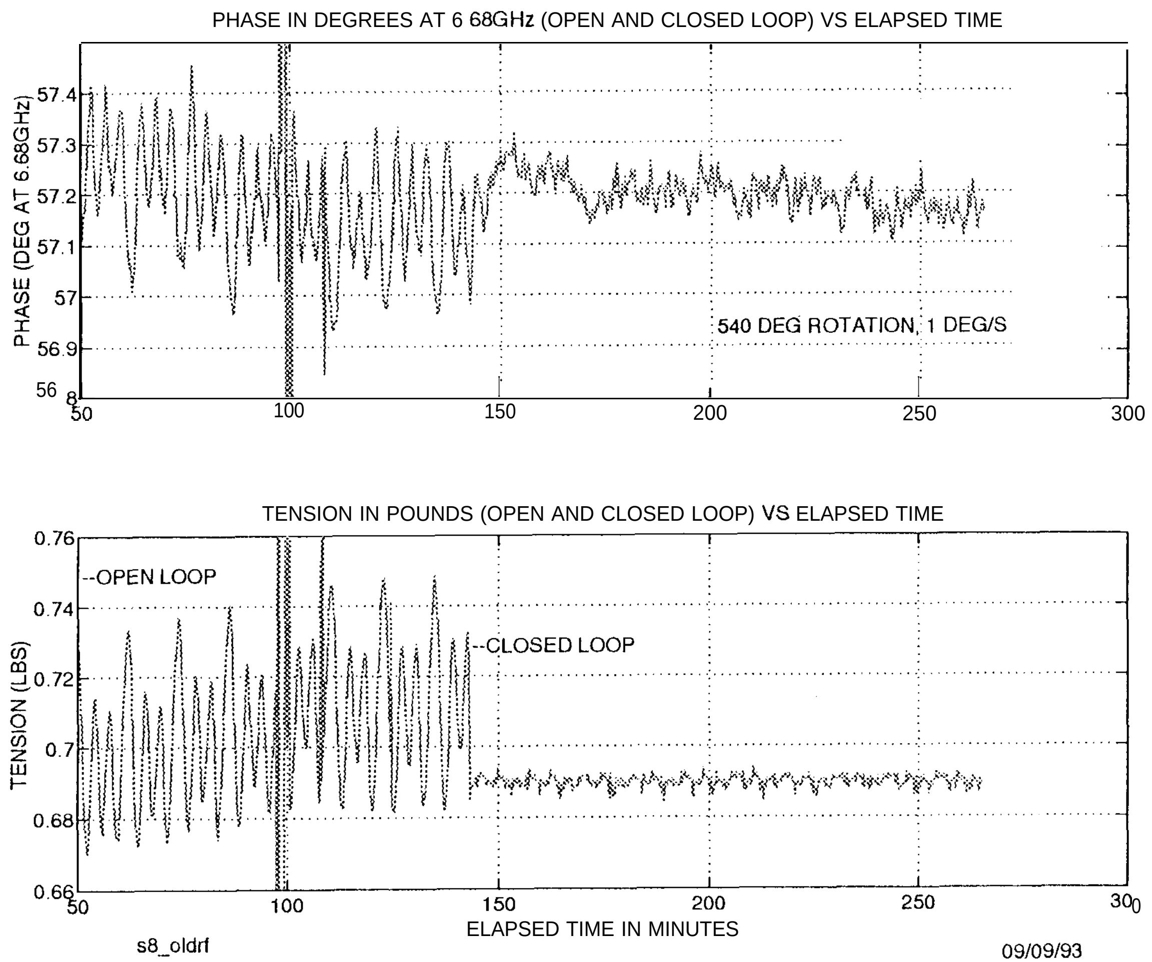


Figure 3 CABLE WRAP TEST INSTRUMENTATION - **SIMPLIFIED** BLOCK DIAGRAM



igure 4 TENSION AND PHASE VS ELAPSED TIME - OPEN AND CLOSED LOOP

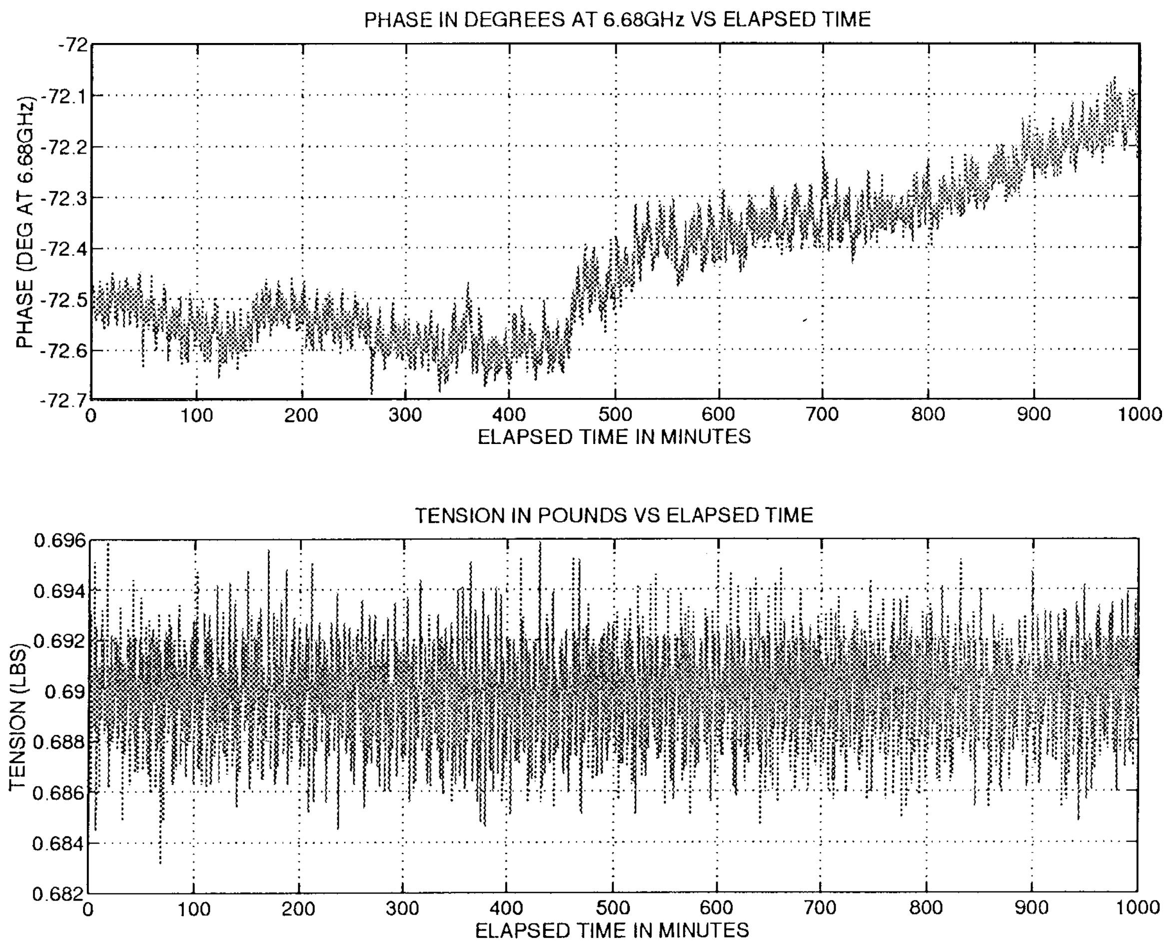


Figure 5 **TENSION AND PHASE VS ELAPSED TIME: LONG-TERM MEASUREMENT**

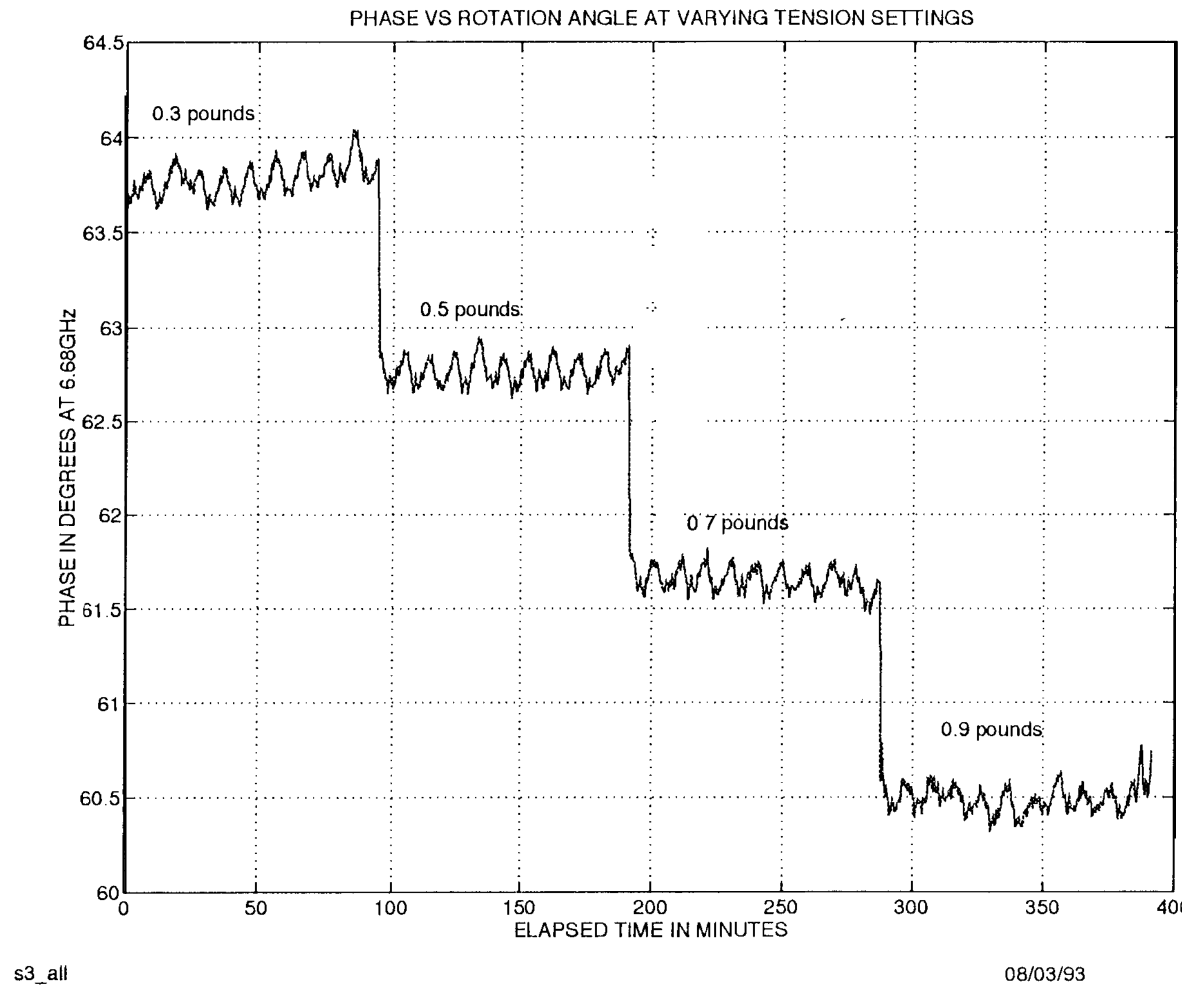


Figure 6 **PHASE VS ELAPSED TIME WITH VARYING TENSION SETTINGS**

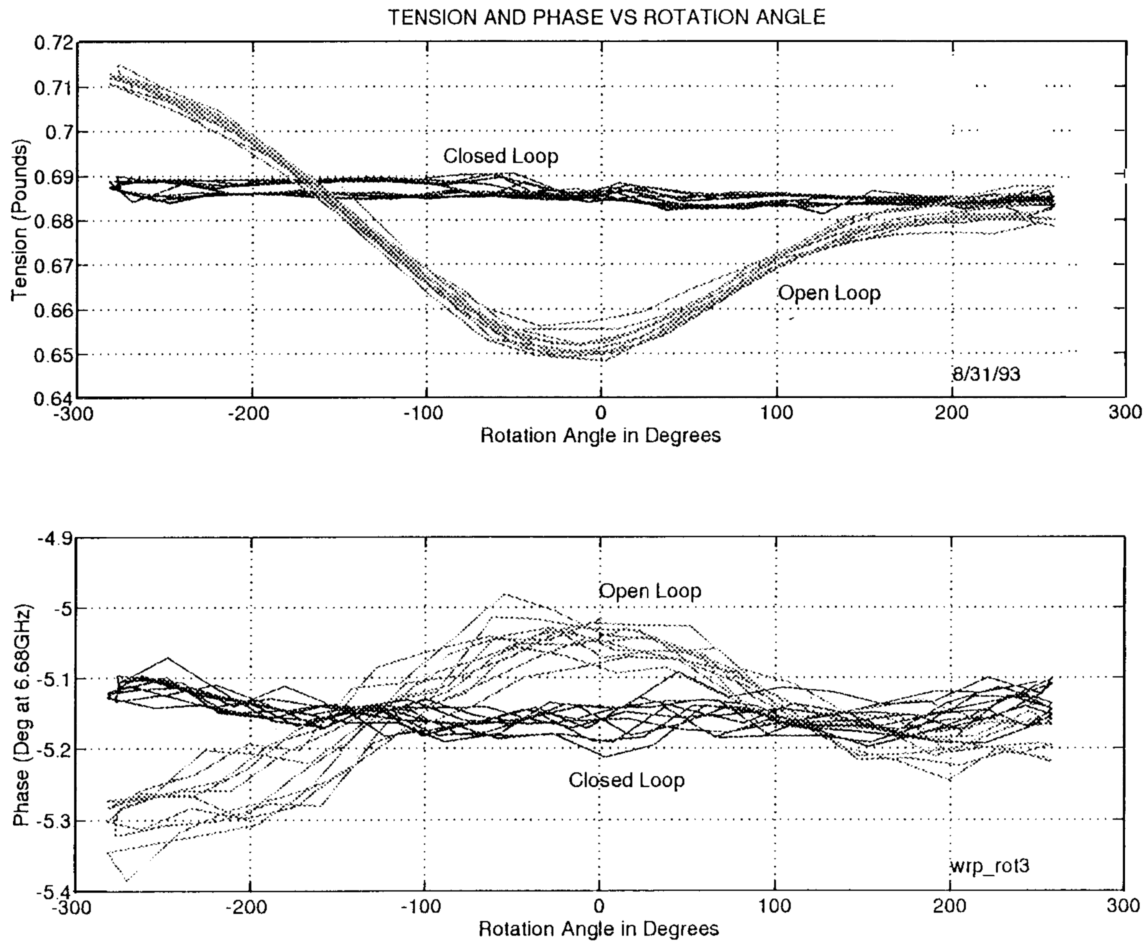


Figure 7 TENSION AND PHASE VS ROTATION ANGLE

APPENDIX A

PMAC TENSION SERVO PROGRAM LISTING
R. CALDER

```
CLOSE DELETE GATHER DELETE TRACE
OPEN Prog 5 CLEAR
,
, TENSION SERVO 9/1/93 REC
,
, Inner loop is PID with proportional 4000000, derivative 1000, integral 4000
, 440 usec servo cycle time (default)
, outer loop is driven by this program
,
, M202 is the converted ADC input @ 21 kHz rate
, P159 is the desired tension in lbs.
, P160 is the converted tension
, P162 is the digital low-pass filter scale factor
, P161 is the tension loop error
, P158 is the error scaling factor
, M361 is the desired-position register (inner loop servos to this position)
,
P158=4
P159=0.7
P160=P159*32767/10*1.01 ; Set for appropriate tension
P162=.9                 ; filter scale factor A of Yi=A*Yi + (1-A)*Xi
p161=p150-m202
while (1<2)
   p161=P162*p161+(1-P162)*(P160-m202)
   M361=M361+(P161*P158)
END WHILE
CLOSE
```