National Radio Astronomy Observatory
Tucson, Arizona
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MEMORANDUM

To: D. T. Emerson and J. M. Payne

From: P. R. Jewell PRJ

Subject: Plan for Pointing Improvement

We must make decisions fairly soon about any pointing improvement projects we intend to initiate this summer, so that we will have time to order and receive components. In this memo, I have reviewed the pointing problems, the status of projects already underway, and the projects I would like to pursue this summer. I am hoping that John will take a fresh look at the problem and suggest some additional approaches. I hope I do not have to convince anyone of the urgency of efforts to improve our pointing accuracy.

I. THE POINTING PROBLEM

We are currently experiencing the following pointing problems, listed in order of severity:

i) Non-repeatable pointing at the same place in the sky. Of late, this has been a gross problem that has discouraged observers from even attempting observations at wavelengths shorter than 3 mm. The worst problem is in elevation (see Figure 1).

ii) A sharp change in pointing offsets at transit (the "clunk" effect), both north and south of the zenith.

iii) Hysteresis in pointing curves. This can be seen if pointing measurements are taken as an object moves across the sky, from rising to setting. It can also be seen from optical pointing data as measurements are taken up and down in elevation.

iv) Inadequacies in the pointing model. There is evidence that additional terms are needed in the pointing model to account for a 2θ tilt term in the azimuth bearing and for horizontal translation of the prime focus, to name two effects. At present, these are second order effects that needn't be addressed until (i) through (iii) above are improved.

It seems that the pointing has actually gotten progressively worse during the course of this observing season, and that the problems have changed in nature during the season. Currently, the big problem is non-repeatability of elevation pointing. Last month, the big problem was the "clunk" in pointing offsets as sources went through transit. The month before it was hysteresis in offsets as objects were tracked across the sky and up and down in elevation. All of these problems may still be present. One thing that is indisputable is that the pointing is BAD!

Analysis of the bad pointing is currently very frustrating because we have so few diagnostic tools in place to isolate or compensate for telescope behavior. The problem is much the same as an engineer would face in trying to fix a faulty piece of electronics without benefit of a voltmeter, oscilloscope, or any other test equipment. The general plan outlined below is to build up appropriate diagnostic and compensatory instruments.

II. GENERAL PLAN FOR POINTING IMPROVEMENT

The most likely sources of pointing problems (for now, assume equal likelihood for each) are

a) Movement of the prime focus from thermal distortion of the feedlegs or backup structure;

b) Changes in the tilt of the azimuth structure resulting from runout in the azimuth bearing, worn bearings, or flexure in the yoke arms;

c) Movement in the Sterling mount or in subreflector positioning.

This is certainly not an exhaustive list of possible problem areas; others include (not in any order of likelihood)

d) distortion of the dish and backup structure;

e) slippage of the hub relative to the elevation mount;

f) flexure in receiver mounting plates, mirror mounts, or the receiver boxes;

g) twist-up of the elevation axle;

h) faulty encoder electronics or fatigued shaft couplings;

i) faulty subreflector electronics;

j) errant or imprecise computer calculations of source or planetary positions, or of the pointing model.

We should take a look at each of these, but I would like to concentrate on (a) through (c) first. We have previously outlined the following general line of attack for these problems:

1) Install instruments that will measure changes in the mechanical attitude and temperature stability of the most important structural components of the telescope [items (a) through (c) above];

   Results from these instruments could be used in two ways. If poor pointing can be correlated with particular mechanical defects or instabilities, we might be able to correct them in a fundamental way (e.g., better insulation, tightening of bearings, etc.). Failing a fundamental cure, then the instruments should provide the information necessary for real-time compensation of pointing errors.

2) Develope an auxiliary optical telescope pointing system that can be used to quickly characterize pointing properties and to correlate pointing changes with the indications of the instruments in (1). This system might also be used as an automatic pointing/guiding system.

The optical telescope thus has two roles, to work in concert with the instruments described in (1) and to provide an independent positioning system if the results of (1) aren't altogether successful.

III. SPECIFIC PROJECTS UNDERWAY OR PROPOSED FOR THE SUMMER

A. Instrumentation Projects

The instrumentation projects that are currently underway are

- o the laser quadrant detector for feedleg motion
- o readout of thermistors on the feedlegs and backup structure
- o an automatic, digital weather station (this project is for monitoring changes in atmospheric refraction)
- o New focus-translation (Sterling) mount

1. Laser Quadrant Detector

The quadrant detector is installed on the telescope and is operating in a total power mode. Data are currently being obtained and an attempt is being made to correlate the results with radio pointing. The laser mount was recently reinforced to reduce or eliminate bending as the telescope is tilted over in elevation. Measurements taken so far indicate (i) a large amount of scatter (>15") in each coordinate and (ii) an unexpectedly large variation in the X (horizontal) direction as the telescope tips vertically in elevation. We don't know at present if either of these effects indicate real excursions of the prime focus or are some instrumental effect of the measuring system. Three things need to be done this summer:

a) turn the instrument into a switched-power system to eliminated any possibility of stray-light-induced noise;

b) get the output of the device digitized and into a computer (either the VAX or a PC);

c) think of some independent way to confirm the X-movement of the apex (e.g., strain gauges, theodolite or other optical sighting device, or maybe an independently mounted quadrant detector). If the apex is translating in the X direction, pointing equations should be modified to account for it.

2. Dish and Feedleg Thermistors

This simple project has been in the works for at least two years but never seems to get done. We have evidence that some of our pointing changes are correlated with time of day, which must mean temperature. To investigate this problem, we need to automatically read the thermistors and record them in some computer (VAX or PC). The thermistors are all installed on the telescope (5 per feedleg and several on the backup structure and hub). Bud and Antonio have sketched out a plan for digitizing the thermistor output in a FEDAL and shipping it out on a GPIB line (see Figure 2). This seems a fine plan and I hope it can be finished this summer. Jobs remaining are:

a) Finish construction of the FEDAL's;

b) Program the data acquisition from the GPIB (on a PC or the VAX).

3. Weather Station

The digital weather instruments were purchased and packaged about a year ago but have never been installed at the site. Antonio is now working diligently to complete the project. The plan is as follows: the temperature, humidity, and pressure sensors will be placed in an enclosure near the weather tower at the site. The analog signals will be digitized in a FEDAL and sent to the dome through a fiber optic line serving as a GPIB (see attached figure). This system can also be used to digitize the signals from the 225 GHz tipmeter and the future tracking IR hygrometer. I have seen pointing jumps of 5-10" that I suspected were from refraction changes. I do not believe these to be a major source of our pointing problems, although we should eliminate whatever problems we can. I hope this project can be completed this summer. Jobs remaining are

a) Finish the FEDAL's;

b) Package the instruments and place them at the site;

c) Run a fiber optic line from the weather tower to the dome (this involves laying electrical conduit under the road);

d) Program the data acquisition from the GPIB.

4. Tiltmeters (Inclinometers)

This is a new project. As I have described in the past, I would like to follow the lead of the VLA and place sets of orthogonally mounted tiltmeters on each yoke arm of the telescope, just below the elevation motor/axle mounts. Having these two sets would provide some redundancy in measurement of the azimuth bearing and would also provide independent information about the yokes. The intention is that these tiltmeters would indicate excursions from the mean tilt profile of the azimuth structure and that these deviations could be fed back to the tracking computer for real time corrections.

[Incidentally, some concerns were expressed previously that one could not use the tiltmeters while tracking because the centripetal acceleration would affect the reading. At *tracking* rates, centripetal acceleration is completely negligible compared to gravitational acceleration, producing a change of $<10^{-3}$ arcsec; the effect is quite noticeable (5-10") at *slewing* rates, however. I have gone through the calculations for the acceleration terms, and have confirmed it empirically with the Talyvel.]

I have collected literature from 11 manufacturers of inclinometers and have summarized my findings in Table 1. There are two basic types of inclinometer. The first has a pendulum mass which is suspended between inductance coils. As the pendulum tilts, the inductance changes which produces a change in the output voltage. The second type consists of a vial containing an electrolyte and three electrodes. As the vial tips, the resistance across the electrodes changes, which produces a change in the output voltage. The electrodes must be excited with AC since electroplating will occur for DC.

I find three models of interest: the Schaevitz LSXH-1 (pendulum type) and the Spectron RG-33T (electrolytic), and the Fredricks Series 0727 (electrolytic). The new Talyvel-3 is also quite accurate, but too expensive. The Schaevitz is of traditional design and is of the type used at the VLA for their tiltmeter package (they are using an older model Schaevitz). I am quite intrigued by the electrolytic levels. They are much cheaper than the Schaevitz, but seem to have equal or better accuracy. A possible drawback of the electrolytic levels is that they are inherently nonlinear devices (voltage vs. angle), and are intended primarily as "nulling" devices. Hence they don't function particularly well as absolute levels or as inclinometers over wide angle ranges (my interpretation here). Nonetheless, what we require is accuracy of 0.5 - 1.0 arcsec over a measurement range of only 1-2 arcmin. I think the electrolytic levels might function very well as inclinometers in this application, since nonlinearities may be negligible over such small ranges. In addition, we should be able to calibrate them against our Talyvel-2, which is a good absolute level/inclinometer, and make any needed corrections in the computer. The manufacturers tell me that the signal conditioning units are essential for high accuracy. These units supply the exciting AC, and also the demodulation and rectification of the output to DC. I would like for John to take a look at these electrolytic levels with me. We might want to order one for tests before buying more.

As mentioned above, the VLA is also conducting a program to outfit a few of their telescopes with tiltmeters. I have recently been in touch with Peter Dewdney (now at Penticton) and with Rick Perley. They have found that their Schaevitz model was rather sensitive to changes in ambient temperature. They have thus spent considerable time developing a temperature control package. Perley claims that the tiltmeter is now completely isolated from outside temperature changes. Jack Campbell has sent me detailed schematics of the VLA tiltmeter package.

Here is what is required for the inclinometer package:

a) Select a model; test one if necessary; buy 4 units eventually.

b) Construct a rigid mount that can be bolted to the top of the yokes.

c) Construct a temperature-controlled, environmentally-sealed package (2 boxes, containing 2 inclinometers each).

d) Digitize the output DC signals in a FEDAL, send to VAX or PC along a GPIB line.

e) Write software for data acquisition.

f) Calibrate the units.

5. Focus-Translation Mount

I suspect that many of our pointing errors originate with the Sterling mount or the subreflector positioning electronics. The project to replace both the mechanical and electronic components should be given high priority. Some, but not complete, renovation of electronics is planned. Jeff will do the mechanical work this summer. Antonio plans a minor upgrade of the electronics this summer. If possible, the timescale for a major upgrade of the electronics should be accelerated. In particular, I would like to see the positioning of the east-west and north-south translation stages in a servo loop with the laser quadrant detector. I would also like to see the positioning of the nutation mechanism of the subreflector made as precise and reliable as possible.

B. Optical Telescope System

Our optical telescope package has already demonstrated its worth. We can obtain in an hour the number of points it takes a day to obtain in the radio. So far, we have conclusively demonstrated the hysteresis problem optically and have shown that the pointing is good over at least a one-hour period. This system is an extremely powerful diagnostic of pointing properties and I would like to see it nurtured through to maturity. Here are the current deficiencies that should be corrected in the next iteration:

1. The current telescope, Barlow lens, and camera system is limited to stars of magnitude ≤ 5.0 (and many listed at $m_v = 5.0$ are not usable. North of the zenith, there are very few astrometric stars brighter than $m_v = 5.0$. This makes it very difficult to do optical pointing in the north, so we aren't getting needed information in that area. We need a more sensitive system. This is most easily achieved by purchasing a new telescope.

2. The current crosshair measurement system is a good first system. However, it is a bit slow and tricky to use, and some of the operators seem to make erroneous measurements with it. To integrate the optical telescope as a standard piece of hardware, we need a fully-automatic data acquisition system. This can be achieved with a frame grabber.

a) New Optical Telescope

I would like to upgrade our pointing telescope to a 8-10" Cassegrain telescope. Currently, we have a 80 mm refractor. From the square of the ratio of diameters, we might expect to go about 2.5 magnitudes deeper with an 8" reflector. This improvement is about what we need. However, looking ahead to an automatic guiding system, we might be ahead to get a 10" telescope to get more stars in the field. The focal length of the telescopes is also a consideration. Most of the commercial Schmidt-Cassegrains are f/10, which gives a 2032 mm focal length for an 8" and a 2540 mm focal length for a 10" (Meade offers a f/6.3 system, which, for a 10" reflector, has a 1600 mm focal length). The plate scale of the 8" would then be 0.1015 arcsec/μm and for a 10", 0.0812 arcsec/μm. The pixel separation on the CCD camera is 11.5 x 27 μm (H x V). In the horizontal direction, the plate scale corresponds to 1.2"/pixel for the 8" and 0.93"/pixel for the 10". Seeing on Kitt Peak is often as good

1", so 1"/pixel is appropriate. The current refractor and Barlow lens have an effective focal length of 1820 mm, so the new systems would have a little better resolution, although in the same general range.

I must note that some years ago, Jack Welch cautioned against using a system with folded optics because of sensitivity to vibrations. Based on our experience with the refractor, I am discounting this as a problem; because the tube of the reflector is so much shorter, it can be mounted more rigidly and will have a much smaller moment arm for vibrations to act on. One additional drawback is that the reflector is probably more sensitive to daytime stray light problems than is the refractor. Nonetheless, these catadioptric systems do have light baffles, and with an extended hood, daytime operation should be feasible.

I have obtained the following quotes for optical tube assemblies:

Table 2

Manufacturer	Type	Diameter	f/D	Price
Meade	Schmidt-Cassegrain	8"	10	$500
Celestron	Schmidt-Cassegrain	8"	10	$700
StarLiner	Classical Cassegrain	8"	12	$1375
Meade	Schmidt-Cassegrain	10"	10	$975
Meade	Schmidt-Cassegrain	10"	6.3	$1225
Celestron	Schmidt-Cassegrain	11"	10	$2000

Here is what needs to be done to proceed with this project:

1. Select a model (diameter and manufacturer)

2. Construct a new mount. Jeff Kingsley has made two suggestions of where to mount the new telescope. The first is to mount it from the inner flange of the new focus-translation mount. The optical telescope would then move with the translation stages (this is attractive, but we need to think about it to make sure it is appropriate for what we want to measure). If we want to go with this option, we need to let Jeff know very soon. The second suggestion is that we construct a double tripod mount to go on top of the quadrupod. Dowel pins would be placed in the top of the "dough-nut" so that the telescope could be taken off and replaced without requiring realignment. The mount must have freedom of adjustment in 2 axes. Design of the second option will require some of Jeff's time (2 days ?), and then some machine shop time.

3. A tube extension (acting as an additional light baffle) will be required and a new motorized lens cap will be needed.

4. The camera assembly must be refitted to the exit tube. Either Tom Folkers or Ray Lichtenhan can do (3) and (4).

b) Frame Grabber

A video frame grabber will offer the following capabilities:

1. Fast and accurate measurement of star positions.

2. Better sensitivity (possibly), since images can be integrated.

3. Automated data acquisition, both for pointing runs and for on-line measurements. For on-line measurements during an observing program, the optical system must be as fast and non-intrusive as possible. For example, we can obtain better correlations of optical data with the data generated by the other instruments (e.g., we can make simultaneous optical measurements while taking radio 5-points without taking out additional time.

4. Use as an automatic guiding system.

5. Possibility for ON/OFF subtraction for daytime pointing (in cases in which the camera doesn't saturate),

6. Diagnostics of tracking servo. By taking a fast time series (30 Hz) of the centroid of a stellar image and performing a Fourier analysis of the results, one would have an extremely powerful diagnostic of servo performance and of telescope mechanical resonances. This could be a valuable tool in fine-tuning the new tracker/servo system.

Two groups at Steward Observatory have build frame grabber systems with very similar functions to ours. Richard Cromwell has built a system to analyze seeing effects on Mt. Graham. He downloads a 21 x 21 pixel array into a PC/AT, and fits for centroid at the frame rate of 30 Hz. Gary Schmidt has built a frame grabber system which is used as an automatic guider for the Steward 90" on Kitt Peak. These people have already provided "proof of concept" for our frame grabber proposal. Furthermore, we can probably steal code from one of them to help develop our system, if we chose the same model of frame grabber (Cromwell uses an Imaging Technologies board and Schmidt uses a Matrox).

I have collected material from four manufacturers of frame grabbers, Data Translation, MetraByte, Imaging Technologies, and Matrox. Each of these plugs in to either an IBM PC/AT or PC/XT expansion slot (the AST computer bought for pointing will be required for AT bus boards; currently this PC is being used as a drafting machine). I note that most of the manufacturers also make frame grabbers for the VME bus, but they are considerably ($1-3 k) more expensive. A summary of possible models is given in Table 3.

Table 3
Frame Grabbers

Manufacturer	Model	Bus	Price
Data Translation	DT2853	AT	$1795
Data Translation	DT2851	AT	$1995
Imaging Technologies	PCVision plus PFGPLUS-512-3-60	AT/XT	$1995
Matrox	PIP-512	PC/XT	$1645
MetraByte	MV1	PC/XT	$1595

To pursue the frame grabber, we must

a) Select a model (should be able to reach a decision within 2-3 weeks)

b) Assign someone to program it over the summer (I have Tom Folkers in mind for this).

IV. SUMMARY AND RECOMMENDATIONS

We should try to complete the following projects before the end of summer shutdown. I have listed the main people involved, and a * denotes a new project.

1. * New focus-translation mount (Jeff)
2. Laser quadrant detector (John, Antonio)
3. Thermistor readouts (Bud)
4. Digital weather station (Antonio, Bud, Dennis)
5. * New optical telescope (Tom, Ray, Jeff)
6. * Frame grabber for optical telescope (Tom)

In addition, we should at least have a prototype of the following:

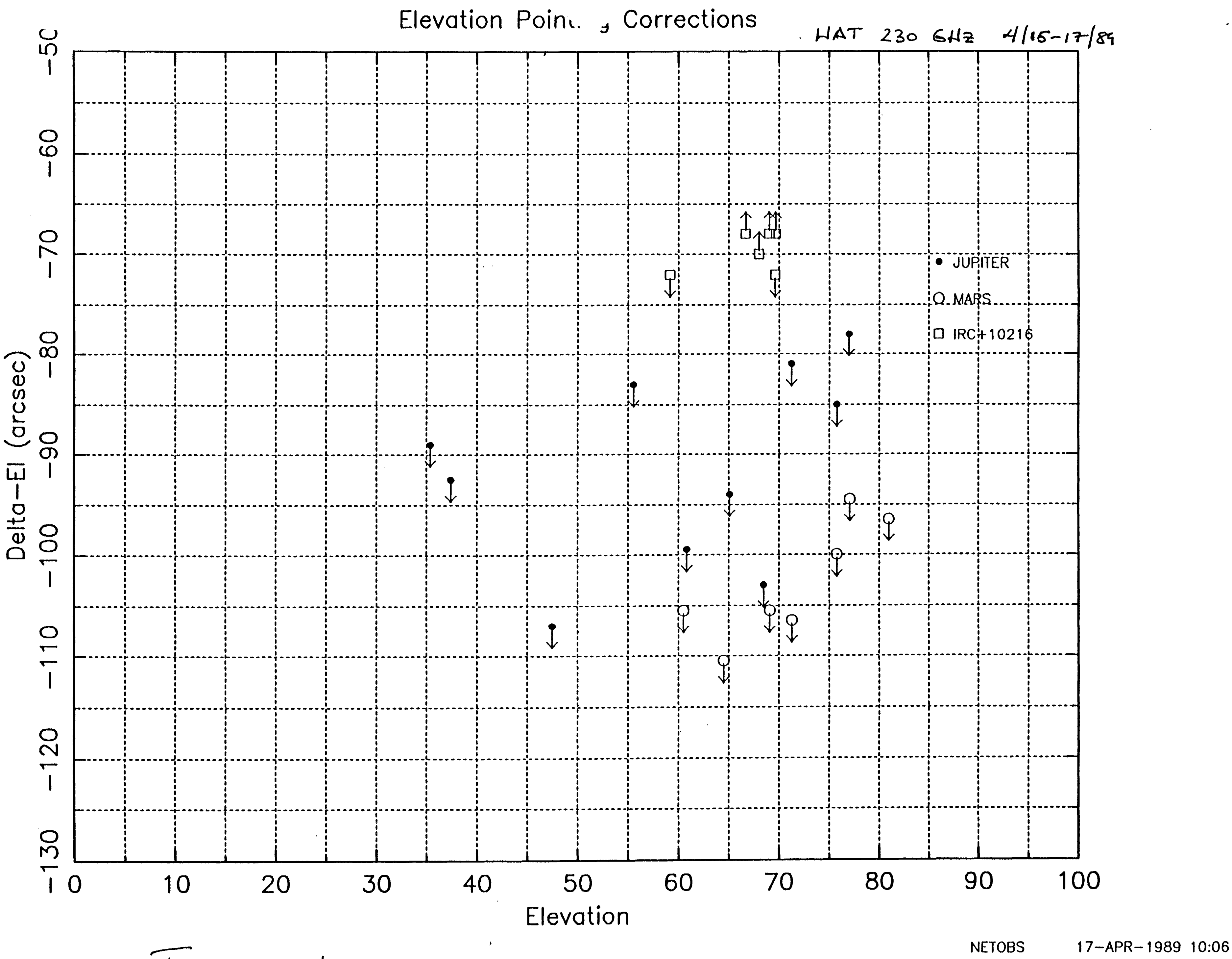
7. * Inclinometer system (John)

The estimated major capital outlays involved for the new projects are listed below. I have not included the new focus-translation mount, which is not strictly a pointing project and is not under my purview. I have also not tried to include machine shop time or miscellaneous electronic components.

Summary of Proposed Equipment Purchases

Inclinometers (4)	$1980 (Spectron model)
or	$5440 (Schaevitz model)
New Optical Telescope	$ 975 (Meade 10")
Frame Grabber	$1995 (Imaging Tech PCVision)
Total	$4950 (using Spectron levels)
or	$8510 (using Schaevitz levels)

In addition to efforts on the new focus-translation mount, I would like to see the equivalent of one full-time engineer -- not necessarily the one and the same person -- devoted to these projects until they are completed. In addition, I would like to make use of Tom Folkers all summer, and possibly Ray Lichtenhan for part of it. Considering the gravity of our pointing problems, this is the <u>minimum</u> acceptable commitment to the project. It must be made clear to the staff that these are <u>priority</u> projects; so far, the message has been just the opposite. If, after one or two months of the next observing season, we are not seeing a dramatic improvement in pointing accuracy, we will have to have a crash program regardless of the impact on other projects.



Elevation Poin.. g Corrections
HAT 230 GHz 4/15-17/89
Delta-El (arcsec)
Elevation
JUPITER
MARS
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FIGURE 1

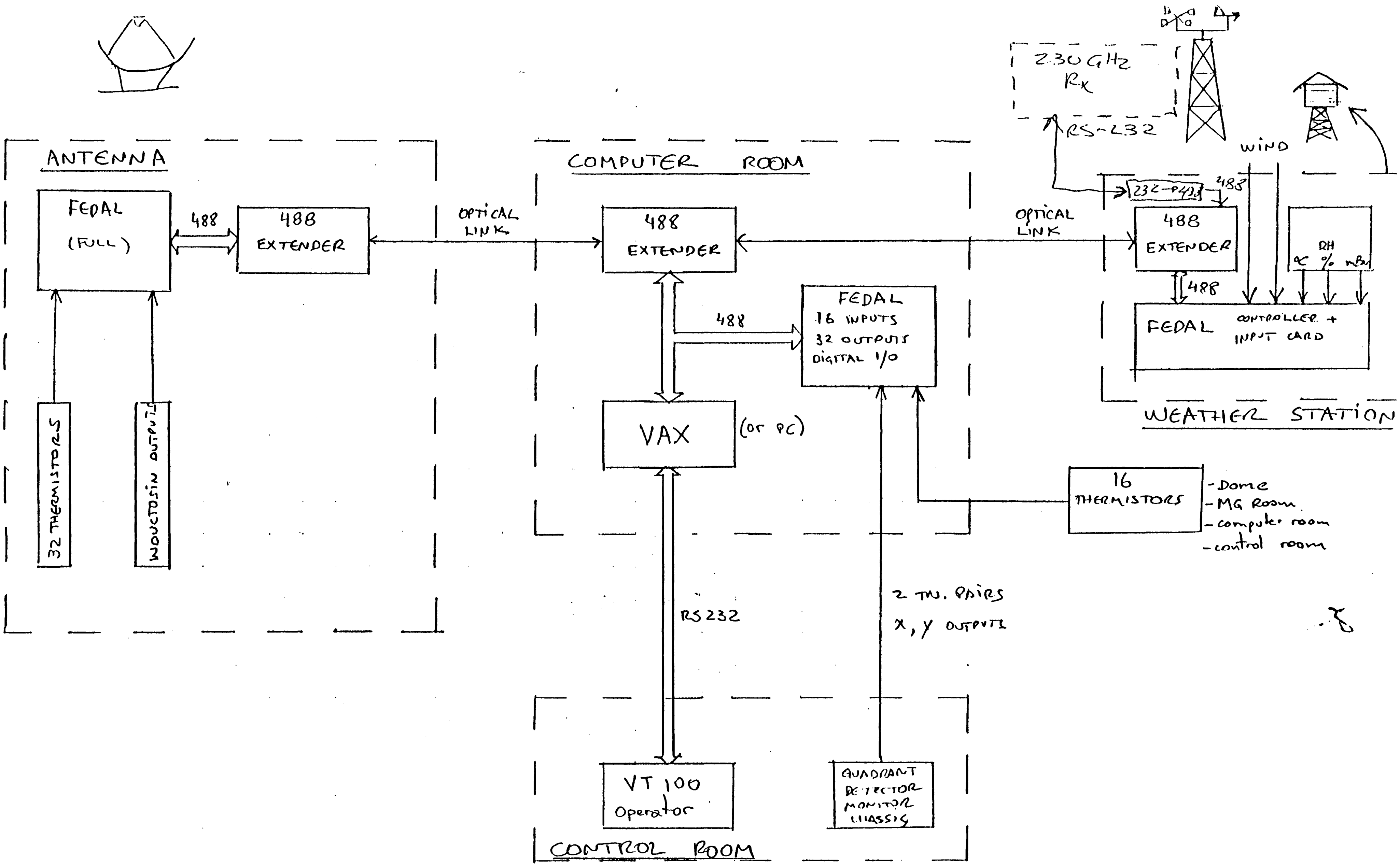

FIGURE 2

BUD/ANTONIO

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TABLE 1

TILTMETER Summary 20-Apr-89

Manufacturer	Model	List Price	Resl. (")	Range (")	Total Error Manuf. spec.	Total Error (")	Linearity (%F.S.)	Hysteresis (%FS)	Type	Comments
Columbia Res.	SI-701BHP	$895	NS	5 deg	0.15% F.S.	27	---	---	Force Balance	JNGE
C. J. Soar Corp.	1710	$399	36	20 deg	N.S.	---	---	---	Magnetic	JNGE
C. J. Ent.	CJI 6021	$495	3.6	45 deg	0.1% F.S.	180	0.1 deg		N.S.	JNGE
Fredericks	Series 0727	$218*	<1	1 deg	3% of reading	1	1.2		Electrolytic	Contender
Gulton									Servo Accel.	Not applicable
Humphrey									Guidance System	Not Applicable
Rank	Talyvel-3	$2700*	0.2	10 min	3 % ?	1.8	3% of Rd.		Pendulum	Good, but $$$$
Robinson-Halpern	685B	$520	"infinite"	6 deg	0.25% F.S.	54			Pendulum	JNGE
Schaevitz	LSXH-1 LSOC-1	$1,360 $1,125	0.1	1 deg	0.07% F.S.	1.9	0.05	0.02	Pendulum	Contender LSOC = VLA model
Spectron	RG-33T-554	$495	0.02	20 min	2% ?	1	2	---	Electrolytic	Contender
West Coast Res.	559	N.S.	18	10 deg	0.29% F.S.	103	0.25	---	Pendulum	JNGE

Key:
N.S. = "Not Specified"
F.S. = "Full Scale"
JNGE = "Just Not Good Enough"

Notes:
The price on the Fredericks 0727 does not include a mounting case
The price on the Rank Talyvel-3 is for the level unit only (meter not included).