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**Planned Holographic Measurements with the Green Bank Telescope**

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The Green Bank Telescope (GBT) is being designed to work at frequencies as high as 50 GHz, with the hope that it may be coaxed to work eventually at ~100 GHz. To achieve good 50 GHz performance, a large effort must be made to ensure that the primary surface of the telescope is, to within ~ few hundred microns, a perfect parabola. The surface panels must be set with great accuracy and gravitational deformations must be compensated for by changing the primary's shape using actuators. One way we can set the panels and measure gravitational deformations is with holographic techniques. The following report describes our recent thoughts on how to make the holographic measurements. It also describes various obstacles we will need to overcome to achieve our desired goal.

1. What do we hope to measure?

Holography is, in many ways, superior to other means of measuring the position of surface panels. Holography usually can measure the surface of a telescope faster and more accurately than the more traditional optical or mechanical measuring systems. Also, measurements can be made at elevations which are typical of observations with a technique similar to the way the telescope will be used for observing radio sources.

The GBT surface panels and the desired surface accuracy (~ 200 microns =  $\lambda/16$  at 100 GHz) dictates that measurements should be made with a 1 sigma noise level of 50 - 100 microns. As noted in section 11 below, we need at least three by three measurements across each surface panel. The size, number, and rectangular shape of the surface panels suggest a minimum of 200 by 250 measurements across the dish of the GBT for a resolution of 0.5 by 0.4 meters. Throughout the rest of this report, we will be using as a minimum requirement an accuracy goal of 100 micron and a resolution corresponding to 200 by 250 measurements across the dish. As illustrated below, doubling the desired resolution and halving the desired surface accuracy, while highly desirable, may prove too difficult or time consuming to achieve.

In addition to setting the surface panels, originally we were thinking of using holography to measure the deformations of the surface under various gravity loads -- that is, to measure what the dish does at various elevations. If the dish is set well at one elevation, the requirements at other elevations can be relaxed quit a bit. For example, we would probably only need at most 128 by 128 measurements (and maybe as few as 32 by 32) across the dish with an accuracy of 100 to 200 microns. As explained below, the cost in instrumentation for obtaining these measurements, even though the requirements are less stringent than for panel setting, can be quite large. We are lucky in that other means may be available to us for making the measurements of deformations (see section 13).

## 2. Which holographic method do we use?

At present, two different holographic methods are known to work.

The more radical method, phase-retrieval holography, requires a source with a high signal strength. The method requires a single receiver and no additional hardware but does require some very sophisticated software and a large amount of computer power. NRAO has no experience with this method and the results at other observatories from phase retrieval are not any better than the traditional methods. It has not been tried for such high resolution measurements as we need for the GBT.

The traditional method requires not only a receiver mounted on the telescope but also a second antenna which is used as a phase and amplitude reference. A correlator of some type is needed to cross-correlate the signals from the two antennas. The hardware requirements are, therefore, more than those for phase retrieval but the necessary software is much simpler, the necessary computer power is trivial, and the measurement technique is much simpler in nature. The desired accuracy and resolution for the GBT is only slightly more stringent than past experiments using this method. That is, it is less of a gamble.

While the hardware for traditional holography may prove to be more expensive than for phase-retrieval, we would have far less programming and learning to do for traditional holography than for phase retrieval. The bottom line is that, once one includes total number of personnel hours, traditional holography for the GBT probably would prove to be the cheaper alternative. Also, phase-retrieval holography is still something of a black art and may be somewhat of a gamble.

In the rest of this report, we will assume that we will be performing traditional holography.

## 3. What do we use as a source of radiation for the holography experiment?

When it comes to sources of radiation for holography, a great number of alternatives are available, all of which have been tried and proved successful.

### a. Local transmitters

One could place a radio source at any desired frequency atop one of the mountains surrounding the GBT. This places the source position, strength, frequency, etc. completely under our control. However, the transmitter would be in the telescope's near field, which would require additional software with which NRAO has no experience. Also, most of the local mountain tops are probably under the 5 deg. lower elevation limit of the GBT and would be unreachable with the GBT. The cost of the transmitter is minimal since most of the equipment is already available and very common in Green Bank. Besides the visibility problem, the measurements would be made when the GBT would be pointing close to the horizon, a non-typical observing orientation. Furthermore, data would only be available from that one atypical elevation angle.

### b. Astronomical sources

Holographic measurements have been performed using strong astronomical masers or continuum sources. However, the accuracy and resolution needed for setting the surface panels has never been achieved (or attempted) using such cosmic sources. The sources may prove useful for the less stringent measurement of the dish deformations. The choice of sources (and their wavelength) includes:

OH masers (18 cm)  
Methanol masers (5 and 2.5 cm)  
Water masers (1.3 cm)  
Any strong continuum source (e.g., 3C84, 3C273, 3C274).

The accuracy of a holographic map is proportional to the wavelength of the observing frequency so the OH masers would be least desirable. The water masers are strongest and highest in frequency but, at the high frequency end, we will be plagued with pointing problems (see section 12); the methanol masers are a few times weaker than water masers but their lower frequency would mean fewer pointing problems. A continuum source could be used at the frequency where it is strongest but such measurements would require a different, wide-band correlator than would be needed by the narrow-line maser sources. We assume that we cannot afford to build both a wide and narrow band correlator and, as shown in (c) below, we probably will be using a narrow-band correlator. Thus, continuum sources may be eliminated from our consideration.

One advantage of astronomical sources is that they can be found at a wide range of positions and elevations, essential for measuring surface deformations but of limited use for setting surface panels. The sources are weaker than those described in (a) above and (c) below and would not provide the necessary signal strength for panel setting but, if a large enough reference antenna was available, would provide sufficient power for measurements of gravitational deformations. One disadvantage is that they follow the sky's rotation and we would need to build a reference antenna on a mount that would track the source. The pointing accuracy of the mount is not very great (a few 10's of arcmin) but its cost, plus the cost of the software for moving it, the encoder and servo-systems, etc. appears to be very high. Other means may be available to measure the deformations (section 13) so we will dismiss for now measurements using astronomical sources.

However, we think we should not design out the possibility of ever using astronomical sources since the methods described in section 13 may not pan out and we may need to fall back on using astronomical sources. We suggest that we think about the hardware and software for such a mount but do not purchase it yet.

### c. Geo-stationary and Geo-synchronous Satellites.

Several geo-stationary satellites with plenty of signal strength are available at both 4 and 12 GHz. The 4 GHz satellites are less desirable than the 12 GHz ones because of their lower frequency -- the accuracy of a holographic map is proportional to the observing wavelength. However, more 4 GHz satellites are available for our use. Both sets of satellites can be found at elevations, as seen from Green Bank, of about 45 degrees and lower (i.e., typical elevations of astronomical observations). However, from Green Bank, no geo-stationary satellite can get above about 45 degrees elevation. These satellites move relatively slowly (a few arcmin per day) so the reference antenna need not track the source -- we would only need to point the reference antenna once, even by hand, and lock it in place. Other considerations about the reference antenna are discussed in section 4.

Geo-synchronous satellites have many of the properties of geo-stationary satellites except that they move during the course of a day through a rather large (many degrees across) analemma pattern. The reference antenna, as well as the GBT itself, would need to follow the satellite through this pattern during the course of the day. Because of their high-inclination orbits, it is possible that the satellite would achieve elevations greater than 45 degrees but only luck would provide us with a satellite that approached 90 degrees elevation. In principle, the same satellite could be used to measure the surface of the GBT at a few elevations. For example, the satellite the 12-m traditionally uses, LES-8 (38 GHz transmitter), would range from something like 10 degrees to 60 degree elevation as viewed from Green Bank. Because of their wild motions in the sky, we would need very accurate ephemerides for geo-synchronous satellites, something we will not need if we

use geo-stationary satellites. Also, the GBT control system would have to perform the necessary pattern of observations for holography (section 10) while following a moving source.

In the case of LES-8 and similar satellites, we would need to contact those in charge of the satellite to provide a signal for our use. On the other hand, most of the 4 and 12 GHz geo-stationary satellites are used as television transponders and have signals always available. These signals are modulated, but our experience in Green Bank with the 140-ft and 45-ft holographic experiments indicated that some transponders have very simple modulations and that a modulated signal only reduces slightly the signal-to-noise ratio in the final holographic map. Thus, we can eavesdrop on any of the geo-stationary satellites and need not make any special arrangements with the companies that manage the satellite systems. This will prove essential because of the extended time we expect will be needed to perform the holographic measurements (sections 10, 11, and 12).

We are at present not tied to any frequency or satellite and we could, with little effort, switch from using one kind of satellite to another. Geo-synchronous satellites mean more work for Monitor and Control (and for data analysis) but the control software should be written with geo-synchronous satellites in mind. In all cases, the transponder signals are narrow band (10's of kHz) so the necessary correlator would have to handle these small and undemanding bandwidths. By far, the 12 and 4 GHz satellites have power levels sufficient for the high accuracy, high resolution holography maps even with the use of a simple, small feed horn as a reference antenna (section 4). LES-8, due to its high frequency and the pointing problems we anticipate (section 12), will be unsuitable for our use initially.

Although the literature indicates a few 12 GHz satellites at various elevations (as seen from Green Bank), we found, in 1987 when we did the 140-ft holography experiment, only three satellites of sufficient strength for holography -- all three were located at elevations near 45 degrees and near the meridian of Green Bank. We should probably use the 140-ft or the 45-ft telescope to try to hunt up 12 GHz satellites at lower elevations that have been launched since 1987 and that have sufficiently powerful transponders. With such a set of satellites at various elevations, we could not only perform the high accuracy holographic measurements but also the deformation measurements for elevations below 45 degrees (section 13).

For the rest of this report, we will assume we will eavesdrop on the normal transmissions of a 12 GHz, geo-stationary telecommunication satellite. This choice is the most arbitrary one we have made so far, but choosing a different frequency or type of satellite will have minimum repercussions.

#### 4. What do we use as a reference antenna and where do we place it?

Once one chooses the type of source to use for the holography, the type of reference antenna is also pretty well determined.

If we eventually have to use astronomical sources, even the low resolution, low accuracy holography maps would require a one to few meter reference antenna. The reference antenna probably has to be located south of the GBT and out of its 'shadow' on a mount which can track the sky's rotation. Note that even a moderate size reference antenna cannot be located on the telescope structure since the size of the holography maps we will need to make will far exceed the beam-width of the reference antenna -- [i.e., the satellite would move out of the field of view of the reference antenna as the GBT went through the pattern of a holographic map (section 10)]. We could use the 140-ft or any of the 85-ft antennas as a reference antenna but the distance between the GBT and the reference antenna would produce phase errors in the holography map (i.e., extra noise) because of the different paths the signals would take through the earth's atmosphere. Moving 85-3 closer to the GBT would help but is probably impractical. In any case, the closer the

reference antenna is to the GBT, the better the measurements will be. As pointed out above, we will probably not use astronomical sources so we won't initially need a large reference dish.

The 4 and 12 GHz telecommunication satellites, our most likely sources, have sufficient power that a small feed horn could be used as a reference antenna. The horn could be placed on the GBT structure and could move along with the telescope during the course of the holographic map as long as the beam-width of the reference horn is larger than the anticipated size of the holographic map. The maximum diameter of the feed is independent of frequency and must be less than the dish diameter divided by the number of resolution elements we want across the dish. For the holographic maps we want to make, this amounts to maximum feed diameter of about 0.3 meters.

An alternative for satellites would be to mount the reference horn stationary on the ground near the GBT. This has no advantages over mounting the horn on the dish (except a bigger horn could be accommodated on the ground), and introduces extra noise in the holographic measurements due to different atmospheric paths, differential heating and cooling of IF and LO systems, etc.

The feed horn mounted on the GBT must have a clear view of the satellite throughout the course of the holographic map. Roger Norrod will look into the problem of where to mount the reference horn. So far, the outer, dish-facing wall of the feed cabin looks like a good place for the horn. The reference horn and receiver could be a permanent fixture on the GBT, ready to be used whenever the need arises. Also, placing the reference receiver as close to the signal feed horn will minimize costs (e.g., same LO multipliers, etc.) and provide the same environment for IF and LO cables so as to minimize such factors as differential heating of cables.

Thus, we anticipate using a small reference feed horn mounted to the dish side of the feed cabin.

#### 5. Should holography be done at Gregorian or prime focus?

The signal feed horn for the holography experiment could be either at the Gregorian or prime focus of the GBT. The 'advantages' of the prime focus are the optics are simpler and you concentrate only on the surface errors of the main reflector.

At Gregorian focus, you will measure the combined errors of primary and secondary surface and won't be able to decipher what errors arise where. [Note: for symmetrical telescopes, one could rotate the secondary between holographic measurements in order to decipher whether a particular error was due to the secondary or primary; the offset design of the GBT, and its asymmetrical secondary prevent us from successfully using this technique.] Thus, occasionally we will be adjusting the primary panels to correct errors in the secondary. The resulting primary probably will not be as perfect a parabola as we could achieve if we made measurements at prime focus.

However, astronomical observations will be made at primary focus only at long wavelengths ( $> 15$  cm) where the errors introduced in the primary surface by Gregorian holographic measurements will be unimportant. At short wavelengths ( $< 15$  cm), when the Gregorian focus will be used for astronomy, the errors of the combined primary-secondary system are most important. In addition, the holographic map made from the Gregorian focus would help us determine any mispositioning of the secondary reflector and Gregorian receivers. Also, the mount for the primary receivers may not be steady enough for the holographic maps we need to make.

Therefore, Gregorian holographic measurements would produce a worse primary than would prime focus measurements; but, in practical terms, high frequency observations from Gregorian focus would benefit from the holographic measurements from Gregorian while low frequency observations would not be harmed. We should, therefore, do our holography from the Gregorian focus.

We have recently realized a problem with Gregorian measurements that we are looking into but is probably not of a serious enough nature to warrant going to primary focus. When the telescope executes the holographic pattern (section 10), the antenna may be tilted far enough from the position of the source so that the signal feed horn may be able to see the source directly. That is, usually the secondary blocks the source's signal from directly entering the signal feed horn. Due to the finite size of the secondary and the large angular size of the holographic maps, the secondary, during the course of a holographic map, may not always have in its 'shadow' the signal feed horn. Roger Norrod and S. Srikanth are looking into how serious this problem is and what we can do about it.

#### 6. What are the receiver requirements?

The signal strengths are so high from satellites that the receivers need not be cooled. Astronomical sources, if we are forced to rely on them, probably would require better receivers. More important than receiver noise is phase stability in the LO's and IF's. Common LO's are desirable. Fiber-optics for the IF would be desirable. The receiver needs to be frequency steerable over the range of the transponders of the chosen transmitting source. Crosstalk between signal and reference receivers must be minimal.

The most likely frequency will be 12 GHz with some possibility of 4 GHz (and maybe a small chance of 22 GHz). Since we will be performing traditional holography and not phase retrieval, two receivers, preferably identical, will be needed. We probably could use the planned 12 to 18 GHz Gregorian receiver as a signal receiver, though the room temperature receivers we are considering only cost about \$200 each.

#### 7. What are the correlator/backend requirements?

Except for continuum sources, the necessary correlator need only work for narrow band (a few 10's of kHz) signals. Minimum integration and data dump times should be somewhere between 0.001 and 0.01 seconds (see section 10). The format of the data that the correlator sends to the control system must be worked out between the builders of the correlator and the designers in Monitor and Control.

The correlator should supply relative amplitudes and phases between the reference and signal receivers (or their equivalent), as well as reference and signal power levels (for monitoring the systems, pointing the GBT, focusing, calibration). A good model for a correlator would be the one used for the 140-ft, 45-ft, and 12-m holographic experiments. Steve White is looking into the correlator design and whether or not we can use the existing holographic correlator.

#### 8. What are the feed requirements?

The signal feed horn must have an exceptionally flat phase error pattern across the GBT primary. Any phase errors in the feed must be measured and will be used in the data analysis. The illumination pattern of the feed should mimic that of the feeds which will be typically used on the GBT; we probably will not need to build a special signal feed but instead will use the same feed designed for astronomical use on the GBT.

The holographic measurements, because of the feed illumination pattern, will be less accurate at the edges of the primary; however, since the feeds which astronomers will use illuminate the edge of the dish less than the center, the surface errors from the outer dish are less important to the overall antenna efficiency measurement. A flat illumination for the holographic signal feed horn would produce a better outer dish than we really need.

The reference antenna must have its phase and illumination pattern measured to a high degree of accuracy. This information will be needed by the data analysis software. The diameter of the feed, if mounted as suggested in section 4 above, should not exceed 0.3 meters (section 4).

#### 9. What are the software requirements?

The Monitor and Control software must be able to accept data from the holographic correlator and use the data for pointing and focusing the telescope. It must pass the data to the analysis system in a yet-to-be-determined format.

The pattern the telescope must perform to make a holographic map is rather complicated. It is close to but deviates slightly from a rectangular grid of points. Unlike the 140-ft experiment, these deviations from a rectangular grid of points are important for the GBT. The pattern depends upon such quantities as distance to the source, distance between vertex and elevation axis, and distance between azimuth and elevation axis.

As shown below, it is imperative that the telescope be able to take the data on-the-fly [i.e., taking data while the telescope is moving at a changing, very fast (20 deg/min) rate in both axes]. Each data point should be tagged with the telescope's current position. The software for driving the telescope through the holographic raster must allow for automatically interspersing, in the middle of the map, occasional calibration and pointing measurements. Also, it is imperative that a map can be interrupted, so that some extra, unscheduled calibration, focus, or pointing can be done, and that the map can be restarted in the middle.

The data analysis subroutines we used for the 140-ft and 45-ft experiment could be modified for the GBT experiment and introduced into the analysis system we will write for the general GBT astronomer. Certain aspects of the analysis we will need for the GBT were ignorable for the 140-ft experiment; these new analysis algorithms have to be written by the data analysis group. My estimate is a few person-months for completing the data analysis software.

#### 10. What will a holographic map look like?

The theory behind holography dictates the spatial sampling interval one must use in the holographic map. Basically, you must produce a 'map' surrounding the transmitter's location in the sky with measurements spaced at about 80-90% of the beam-width of the telescope. For the GBT at 12 GHz, this works out to a spacing of 55 arcsec.

Next, the resolution across the dish depends upon the size of the 'map'. To achieve the desired 0.5 by 0.4 meter resolution (i.e., 200 by 250 resolution elements across the primary), one must sample a region that extends (250x55 arcsec) by (200x55 arcsec) and is centered on the satellite. Thus, the holography map at 12 GHz would be some 3.8 by 3.1 degrees in size. If the reference antenna were mounted on and moved with the GBT, the antenna must have a half-power beam-width that exceeds about 4 degrees (i.e., a diameter less than about 0.3 meters; section 4).

The accuracy of the holographic map depends upon the signal strength of the source, the integration time, and the noise introduced by poor calibration, bad pointing, bad focus, receiver phase instability, atmospheric fluctuation, digitization noise, etc. Our estimates for typical satellite transponders indicate, with a small feed as a reference antenna, integration times much less than 1 msec. Astronomical sources will need 10's of msec with a large reference antenna for sufficient signal to noise.

Most often, the shape of the holography map is close to rectangular. Some past experiments have tried spiral or cart-wheel patterned maps, but it is not obvious that these patterns are any better than the traditional, simple pseudo-rectangular grid.

If the telescope control system is incapable of the on-the-fly method of data taking, then the telescope will have to be moved from one position to another in the map. If one uses 2 seconds for the move and settling time between positions in the holography map, then a single map would take 28 hours plus overhead (more below on overhead). This is an intolerably long time, especially when one considers the number of maps we need to make (sections 11 and 12)

If it can take data on-the-fly, then, if the telescope were to move at its fastest rate (20 degrees/min), and if we allow 30 seconds for turning the telescope around to go from one strip in the map to the next, a typical map would still take slightly under 3 hours. The direction of scanning will depend upon the pointing accuracy and turn-around times of the GBT. At 20 deg/min, if we were to sample data every 15 arcsec (one-fourth of the 55 arcsec separation we need), then integration times can't be any longer than 0.01 seconds. Longer integration times than this would make the maps longer to produce or would have a smearing effect in the final holographic data.

In addition, we must allow for the overhead for calibration, pointing, and focusing measurements. The overhead will amount to about 20 - 30% more time per map. Thus, the fastest holographic maps for panel setting will take 4 hours. For the deformations maps, much less time will be needed [which depends upon whether we use astronomical sources (~2 hours) or strong transmitters (10's of minutes)].

#### 11. What are the practicalities of panel adjustments?

The holographic method has certain limitations. Although it provides high accuracy data, it has problems isolating where on the dish errors occur. This is due to the leakage or smearing effect caused by the point-source response of the holographic measurements. For example, if the dish were perfect except for a single panel being high, the holographic map would indicate that the discrepant panel as well as some of its neighbors were either high or low.

To combat this deficiency in the method, a combination of techniques must be used.

a. The more samples you have per panel the less problem leakage will be in producing false panel setting. Our choice of three by three resolution elements per panel is a MINIMUM. Increasing this to a more desirable 6 by 6, however, would more than quadruple the time needed for a holographic map.

b. Passing the data through 'filters' reduces the effects of leakage but also reduces the resolution of the final map.

c. Iterating measurements and panel adjusting always prove necessary regardless of whether (a) or (b) is tried. That is, you make a holography map (with filtering), adjust the panels, make another map, move the panels, etc.; you repeat this until a map has the desired accuracy.

We anticipate from three to four iterations will be needed for the GBT panel setting maps. The deformation maps, on the other hand, will not need to be iterated since the desired accuracy and resolution is not as stringent as for panel setting. When combined with the number of maps we will need to beat down the noise level (section 12), we pessimistically anticipate something like 30 maps of 4 hours each will be needed. Since maps can probably only be made on calm nights (section 12), it may take us close to a month for holography and panel setting.

## 12. What are the other sources of noise in a holographic map?

Pointing errors are by far the most likely source of 'noise' in our holographic maps. A random rms pointing error of 1 arcsec will produce at 12 GHz about a 60 micron random error in the final holographic map (this error is dependent on beam size and, thus, observing frequency). But it is important to know what kinds of pointing errors are important for holography.

The absolute pointing error of the GBT is not important but the error relative to the satellite position is. Let  $X$  represent the actual position of the satellite and  $X'$  the positions we assume (or measure) for the satellite. Let  $x(i)$  be the  $i$ th positions within the holography map at which we wish to make a measurement and let  $x'(i)$  be the  $i$ th positions at which we actually performed a measurement.

If  $(X-X')$  is constants throughout a map, then the holographic map will be unaffected. It is best to minimize  $(X-X')$  but it is not necessary to do so. The quantity  $(X-X')$  can differ from one map to the next with no ill effects.

If  $(X-X')$  varies slowly throughout a map, and we can measure the change in  $(X-X')$  during the course of a map to better than 1 arcsec, then we can compensate for the errors in the data analysis stage.

If  $(X-X')$  varies quickly or cannot be measured with enough accuracy, then the pointing error would amount to a 60 micron noise level per arcsec of rms pointing error. If the error is Gaussian in nature, both during a map and between maps, then we can reduce the noise introduced by the pointing offset by averaging multiple holographic maps together. If non-Gaussian, then we won't be able to circumvent the pointing problem.

If  $[x(i)-x'(i)]$  equals  $[x(j)-x'(j)]$  for all  $i$ 's and  $j$ 's in the map, then the map will not be affected by the pointing offset.

If  $[x(i)-x'(i)]$  does not equal  $[x(j)-x'(j)]$  for any  $i$  or  $j$ , but if we know, to an accuracy of 1 arcsec (or better), how much  $[x(i)-x'(i)]$  differs from  $[x(j)-x'(j)]$  for all pairs of  $i$ 's and  $j$ 's, then the pointing errors can be corrected for in the data analysis stage.

If  $[x(i)-x'(i)]$  does not equal  $[x(j)-x'(j)]$  for any  $i$  or  $j$ , and if we do not know how they differ, then, if on the average they differ by 1 arcsec, then 60 micron of noise will be introduced into the holography map. If these types of errors are Gaussian in nature throughout a map and vary from one map to the next in a Gaussian fashion, then averaging holographic maps will reduce the noise introduced by the pointing errors. If they are non-Gaussian in nature, then we won't be able to circumvent the pointing problem.

We will also have serious problems if there are any unknown but repeatable pointing errors from one map to another that exceed 1 arcsec. For example, an insufficiently accurate atmospheric refraction correction would be extremely harmful.

Since we will be driving the telescope while taking data, it is not the static pointing error but the high frequency, dynamic (on a time scale of 0.01 sec) errors which are important.

Until the GBT is completed, we will probably not know what kinds of pointing errors it will have and how they will affect the holographic map. In any case, maps probably can only be produced on calm nights (to further the chance of low pointing errors). If we take 10 arcsec as a typical rms error, and we pray that the error is non-repeatable and Gaussian, then something like nine holographic maps of 4 hours each (i.e., three nights of data taking) will produce a single holographic map with a 1 sigma noise level of 100 microns.

Another source of error is the thermal changes to the GBT during the course of a holographic map -- the longer the map, the more likely thermal noise will creep into the holographic map. Again, taking data on calm nights and averaging maps together is the only solution to reducing the noise introduced by thermal affects. We do not know what magnitude error to expect in the holographic maps from thermal affects.

### 13. How can we measure gravitational deformations?

If we choose to use astronomical sources for holographic deformation measurements, then we will have to pay for the necessary antenna mount and software. A few other alternatives exist, however.

First, Lee King ensures us that the deformations of the dish can be predicted from his model of the telescope. All he needs is a single calibration number. If this is true, we may be able to provide that number by performing holography on satellites at only two elevations -- 45 degrees and something well below this. We probably can't use a satellite to give him measurements above 45 degrees elevation.

Alternatively, we could move the panels according to Lee's best guess for the calibration factor for gravitational deformations. We then measure the efficiency of the telescope over a range of elevations. We then try a different calibration number, and again measure efficiencies. And so on. This iterative approach has proved successful for determining the gravitational deformations of the 140-ft and may prove reliable for the GBT.

The last method that comes to mind involves using John Payne's laser ranging scheme to measure the deformations. But this relies on our so-called stage three technology to perform observations during stage one of the GBT's life.

### 14. Summary

The holographic maps, therefore, will have the following properties:

1. Maps for setting the surface panels will have a one sigma accuracy or 100 microns and a resolution of 0.5 by 0.4 meters.
2. We will use the traditional holographic method, as opposed to phase retrieval.
3. The signal source will be 12 GHz transponders of standard modulated signals from geostationary telecommunication satellites. Though, we may need to use astronomical sources or 4 GHz satellites for deformation measurements.
4. A small (0.3 meter diameter) feed horn, mounted on the GBT near the Gregorian receivers, probably will be used as an initial reference antenna, although a large reference antenna on a movable mount may eventually be needed if we are forced into using astronomical sources.
5. The measurements will be made from the Gregorian focus.
6. The receiver, correlator, and feed requirements will not be too strict or expensive to meet.
7. The Monitor and Control group must work with data-analysis and the holographic groups on data taking techniques and data storage formats; some special work will be needed from Monitor and Control and from data-analysis programmers.

8. The holographic map will be a near rectangular grid of points with size 3.1 by 3.8 degrees and with data points spaced about 55 arcsec apart. Maps will take about 4 hours to complete.
9. The process of holography is an iterative one and we must allow about a month for collecting the necessary data and setting the panels.
10. Pointing errors probably will be the major source of errors in a map; thermal effects may also be important.
11. Alternatives for determining gravitational deformations that may be cheaper than holography are discussed in section 13.