Abstract

High-frequency observations are both slowed and degraded by atmospheric opacity, wind gusts, and solar heating. Consequently, the GBT was unable to satisfy user demand for high-frequency observing time. The effective amount of observing time (clock time multiplied by observing efficiency) has been increased by dynamic scheduling using short-term (24–36 hour or 48–60 hour) weather forecasts to match observations with weather conditions. This project note describes our dynamic scheduling method, the ranking algorithm that chooses which observing session in the pool to schedule next, and simulations that compare dynamic scheduling with traditional GBT scheduling. The simulations indicate that dynamic scheduling can increase the effective observing time at frequencies higher than 10 GHz by about 50% without unduly burdening either observers or Green Bank support staff. Observers can be given at least 24 or 48 hours advance notice before their observing sessions start. Also, observers who are unavailable on certain dates (while they are traveling, for example) have the option of temporarily withdrawing their projects from the pool without penalty. We estimate that $\sim 15\%$ of the dynamically scheduled observing sessions at frequencies higher than 18 GHz will have to be canceled at the last minute because the actual weather is much worse than the forecast weather. The resulting gaps can be filled on short notice if $\sim 25\%$ of the low-frequency ($\nu < 10$ GHz) sessions in the pool are available as backups that the telescope operator can run from prepared scripts or by astronomers voluntarily on call. An observing pool containing only one month of observations is sufficient for efficient dynamic scheduling, so dynamic scheduling can shorten the delay between proposal submission and observing by about one month compared with traditional trimester-based scheduling. Dynamic scheduling can also respond much better to rapid-response observing requests. Dynamic scheduling was recently upgraded to include observations in the “3 mm” atmospheric window between 68 and 117 GHz.
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History


5.3 2010 Jul 20. Added Eq. 3a for $\nu < 2$ GHz, increased the frequency in Eq. 10 for lower GBT surface errors, added Eq. 12a and 13a to renormalize tracking efficiency, added Eq. 22a to fit the average
observing efficiency at 3 mm, updated the atmospheric stability limit following DS/PN14.2, and increased the MUSTANG $f_v$ in Eq. 26 from 0.2 to 0.4. (J. J. Condon & D. S. Balser).
1. Introduction

High-frequency observations are both slowed and degraded by atmospheric opacity, wind gusts, and solar heating. Consequently, the GBT had been unable to satisfy heavy user demand for high-frequency observing time. The effective amount of observing time (clock time multiplied by observing efficiency) was increased by dynamic scheduling using short-term (24–36 hour or 48–60 hour) weather forecasts to match observations with weather conditions. This project note is an updated description of our dynamic scheduling method, the ranking algorithm that chooses which observing session in the pool to schedule next, and simulations that compare dynamic scheduling with traditional GBT scheduling. The simulations indicate that dynamic scheduling can increase the effective observing time at frequencies higher than 10 GHz by about 50% without unduly burdening either observers or Green Bank support staff. Observers can be given at least 24 or 48 hours advance notice before their observing sessions start. Also, observers who are unavailable on certain dates (while they are traveling, for example) have the option of temporarily withdrawing their projects from the pool without penalty. We estimate that $\sim 15\%$ of the dynamically scheduled observing sessions at frequencies higher than 18 GHz will have to be canceled at the last minute because the actual weather is much worse than the forecast weather. The resulting gaps can be filled on short notice if $\gtrsim 25\%$ of the low-frequency ($\nu < 10$ GHz) sessions in the pool are available as backups that the telescope operator can run from prepared scripts or by astronomers voluntarily on call. An observing pool containing only one month of observations is sufficient for efficient dynamic scheduling, so dynamic scheduling can shorten the delay between proposal submission and observing by about one month compared with traditional trimester-based scheduling. Dynamic scheduling also responds much better to rapid-response observing requests. New simulations covering the 68 to 117 GHz (a.k.a. the 3 mm band or W band) atmospheric window suggest that up to several hundred hours per year of 90 GHz MUSTANG filled-array observations could be scheduled dynamically.

This project note describes both the traditional and proposed dynamic-scheduling methods for scheduling the GBT (Sec. 2), the ranking equation that automatically selects the best observing sessions based on the weather forecast (Sec. 3), and simulations that compare dynamic and traditional GBT scheduling (Sec. 4).

2. Traditional and Dynamic Scheduling Methods

The primary goal of dynamic scheduling is to maximize the effective observing time on the GBT without unduly burdening either observers or the Green Bank support staff. Maximizing effective observing time is largely a technical exercise in matching observations to the weather. Observations near the water line at 22.3 GHz are especially sensitive to atmospheric water vapor, while wind-induced pointing errors and telescope surface deformations caused by differential solar heating are problems at higher frequencies. Since weather predictions become less accurate as they look farther into the future, the most efficient scheduling method would choose the best observing session remaining in the pool of approved projects whenever the telescope becomes free to begin a new observing session. However, an astronomer is still needed to control (either from Green Bank or remotely) most GBT observations, so that method would require most potential observers to be “on call” at all times. This is an unacceptable burden on observers and Green Bank support scientists, so a compromise was made between efficiency and convenience.
The traditional GBT schedule was outlined weeks in advance, but it did leave room for a limited amount of dynamic scheduling. Only low-frequency ($\nu < 10$ GHz) observations were scheduled during the summer trimester (June through September), when the air is usually too warm and humid for efficient high-frequency ($\nu \geq 10$) observing. During the rest of the year, the human scheduler paired each high-frequency observing session with a low-frequency observing session of the same duration. Two fixed blocks of time, typically separated by one or two days, were set aside for each pair. The high-frequency observer decided which block to take, and the low-frequency observer got the other block of the pair. This decision was made by 11 AM ET of the same day for which observing was scheduled between 17:00 on that day and 24 hours hours later (17:00 the next day). Thus the final GBT schedule was traditionally fixed between 6 and 30 hours in advance, and both observers were “on call” for a few days with as little as 6 hours notice while their session pair was being scheduled.

The pairing method was not very efficient. Neither day of a pair may be good enough for the high-frequency observations, especially at K-band, where the weather is good enough for efficient observing $< 10\%$ of the time. The better day may not be well matched to the particular high-frequency observation because different high frequencies have different weather requirements—a very dry day with moderate winds is good for K band but unusable for Q band, and a calm night with moderate humidity is good for Q band but bad for K band. Both days might be “too good” for the low-frequency observations, wasting a high-frequency observing opportunity. The high-frequency observer used longer-term and less-reliable weather forecasts to estimate the quality of the second time block before deciding which block to pick. Traditional scheduling placed the burden on the high-frequency observers to follow the weather forecasts and understand the effects of water vapor, clouds, sun, and wind on their observations. Many high-frequency observers are not skilled enough to make appropriate decisions based on weather forecasts.

Since dynamic scheduling that relies on short-term weather forecasts cannot predict the telescope schedule weeks in advance, observers may be “on call” to observe on fairly short notice, as little as 6 hours for the traditional pairing system. To minimize the burden on observers and the Green Bank staff supporting them, we decided to increase the minimum notification time from 6 to 24 hours or even 48 hours in our new dynamic-scheduling system. Also, observers who are unavailable on certain dates (while they are traveling, for example) should have the option of temporarily withdrawing their projects from the pool without penalty. In order to give observers at least 24 (or 48) hours notice, the dynamic-scheduling algorithm must rely on forecasts predicting the weather 24–36 (or 48–60) hours in advance. Consequently the actual weather at the beginning of the scheduled observation may differ significantly from the forecast weather. If the actual weather turns out to be acceptable or even “too good” for the scheduled observation, that observation is made as scheduled. This compromise favors observer convenience over observing efficiency. If the weather is much worse than forecast, then the scheduled observation may have to be canceled at the last minute. To avoid “dead time,” a more robust low-frequency backup program is inserted in its place. Backup programs are those programs voluntarily designated in advance as such by the observer. Most can be run automatically from scripts by the telescope operator without observer intervention, but backup observers can also request to be notified when their sessions are about to start. Efficient dynamic scheduling requires a pool of backup programs that can be run from prepared scripts by the telescope operator without help from the observer. Our simulations (Sec. 4) indicate that only 25% of low-frequency ($\nu < 10$ GHz) programs in the pool need to be backups in order to fill potential dead times.
A “fixed session” is one that must be executed during time interval(s) fully specified in advance by the observer. It usually involves another telescope having a fixed schedule, such as bistatic radar with Arecibo. A fixed observing session is simply inserted into the schedule and cannot be moved or preempted. A “windowed session” must be executed within a constrained time range or set of ranges specified in advance by the observer. For example, most pulsar monitoring projects involve windowed sessions to ensure that successive observations are made at roughly the desired intervals (e.g., separated by two weeks plus or minus two days). Windowed sessions may be dynamically scheduled subject to the the windows constraints. To minimize the number of times that the observer must be “on call,” the number of possible windows should not exceed a limit chosen by the observer; e.g., two or three. Routine telescope maintenance can also be dynamically scheduled using either fixed or windowed sessions.

Unconstrained, windowed, and fixed sessions appear to be qualitatively different, so it might seem that qualitatively different dynamic-scheduling algorithms would be required to handle them. However, this is not the case. All session types can be treated as constrained sessions, differing only quantitatively in the numbers of scheduling opportunities open for each. Thus a normal unconstrained session has a large (effectively infinite) number of windows during which it can be scheduled some time in the future, a windowed session has only a few opportunities, and a fixed session may has only one window of opportunity. The smaller the number of remaining opportunities to schedule a session and the larger the session stringency, the more urgent it is to schedule that session, even if it is not currently the “best” session in the pool. Just how much a constrained observing session should be favored to ensure that it will be scheduled sometime within the specified windows can be determined by statistical analysis.

The heart of dynamic scheduling is the algorithm that chooses which sessions to schedule by ranking those in the pool and displaying the highest-ranked sessions so the telescope operator can choose the most appropriate one. Our ranking system is described in the next section.

3. Ranking System

Following Condon & Balser (2007) we assign each observing session remaining in the pool of approved sessions a ranking score:

$$R = (\eta SP_\alpha P^\beta)(l_{eff}l_{HA}l_{st})(f_{com}f_{sp}f_{tp}).$$ (1)

Multiplication is commutative and associative, so the individual factors in Eq. 1 can be ordered, grouped, merged, and subdivided as desired. New factors can be added and old factors can be deleted without altering the relative influence of the other factors. The value of $R$ changes with time, and the algorithm can quickly yield a list of the sessions currently having the highest scores. Normally the highest-ranked session will be scheduled to go on the telescope in the near future. Sessions scoring $R = 0$ (e.g., $R = 0$ if the target source is not up) are unacceptable and never scheduled. Below we describe the individual factors in Eq. 1.

3.1. Observing Efficiency $\eta = \eta_{atm}\eta_{sur}\eta_{tr}$

We define observing efficiency $\eta$ as the ratio of the integration time needed to make a transit observation in the best weather to the time needed to reach the same sensitivity given the actual weather conditions
and hour angle. Efficiency normalized in this way always ranges from zero to unity. These relative times are calculated from the radiometer equation. We divide $\eta$ into three independent subfactors specifying the efficiency contributions of atmospheric opacity, telescope surface errors, and tracking errors:

$$\eta = \eta_{\text{atm}}\eta_{\text{sur}}\eta_{\text{tr}}$$  \hspace{1cm} (2)

and evaluate them separately.

### 3.1.1. Atmospheric Efficiency $\eta_{\text{atm}}$

The efficiency factor representing the emission and absorption caused by atmospheric opacity is (Condon 2007):

$$\eta_{\text{atm}} = \left[ \frac{T_{\text{sys}} \exp(\tau_<)}{T_{\text{sys}} \exp(\tau)} \right]^2,$$  \hspace{1cm} (3)

where $\tau$ is the optical depth through the atmosphere along the line-of-sight from the source to the telescope, $T_{\text{sys}}$ is the system temperature, and the subscript $<$ means “minimum possible value of.” Again, normalizing by these optimum values ensures that $0 < \eta_{\text{atm}} < 1$.

At any observing frequency $\nu$, the zenith optical depth $\tau(z(\nu))$ is predictable from the weather data at [http://www.gb.nrao.edu/~rmaddale/Weather/](http://www.gb.nrao.edu/~rmaddale/Weather/). The zenith opacity during typical summer weather (1.0 cm of precipitable water vapor, 55% cloud cover, and surface air temperature $T = 288$ K) is shown as a function of frequency up to 50 GHz in Figure 1 and between 60 and 120 GHz in Figure 2. The total opacity is the sum of contributions by several atmospheric constituents. The dry air (continuum) and oxygen (pressure-broadened line) opacities are nearly independent of weather, while the water vapor (pressure-broadened line and continuum) and hydrosol (continuum) opacities are quite variable. The ratio of the water-vapor line and water-vapor continuum opacities is nearly constant because both are proportional to the column of precipitable water vapor PWV. When the relative humidity is high enough, clouds of hydrosols (water droplets) form and can dominate the total zenith opacity at high frequencies.

Observations made near the 22.3 GHz water line are especially sensitive to weather, and they should be scheduled only when the sky is clear and exceptionally dry. Conversely, near 45, 70, and 115 GHz the steady oxygen opacity is so high that the observing efficiency is fairly insensitive to moderate amounts of water vapor or cloudiness. Within the 68 to 117 GHz atmospheric window, the water-vapor continuum opacity is always an order-of-magnitude higher than the water-vapor line opacity, and hydrosol opacity generally precludes observations through clouds. Figure 2 shows that water vapor contributes $\tau_{\text{dimer}} \sim 0.1 \times \text{PWV} (\text{cm})$, so $\text{PWV} \lesssim 1 \text{ cm}$ is needed for reasonably efficient observations, and efficiency near 100 GHz improves as PWV declines to $\sim 1 \text{ mm}$, at which point the underlying oxygen opacity dominates.
Fig. 1.—Zenith opacity below 50 GHz during typical summer observing weather. Abscissa: frequency (GHz). Ordinate: zenith opacity (nepers).
Fig. 2.— Zenith opacity between 60 and 120 GHz during typical summer observing weather. Abscissa: frequency (GHz). Ordinate: zenith opacity (nepers).
The lowest frequency at which $\tau_z(\nu)$ is calculated from the GBT weather data is $\nu = 2$ GHz, but the GBT is used at frequencies down to $\nu \sim 0.3$ GHz. The zenith optical depth at $\nu < 2$ GHz is always dominated by the dry-air continuum opacity $\tau \approx 0.0075 \pm 0.0005$. In bad weather, the hydrosol and water-vapor components contribute significantly. Both have opacities proportional to $\nu^2$, so a good approximation to the zenith optical depth at all frequencies below 2 GHz is

$$
\tau_z(\nu) \approx 0.0075 + [\tau_z(2 \text{ GHz}) - 0.0075] \left(\frac{\nu}{2 \text{ GHz}}\right)^2.
$$

(3a)

The optical depth along the line of sight to a target source is

$$
\tau = \tau_z \sec z,
$$

(4)

where $z$ is the source zenith angle given by

$$
z = \arccos(\sin \phi \sin \delta + \cos \phi \cos \delta \cos H).
$$

(5)

Here $\phi \approx +0.6681$ rad is the latitude of the GBT, $\delta$ is the source declination, and $H \equiv (\text{LST} - \alpha)$ is the hour-angle of the source at right ascension $\alpha$. The minimum zenith angle $z_\prec = |\delta - \phi|$ occurs at source transit ($H = 0$), and the minimum possible optical depth for a source at declination $\delta$ is the transit optical depth

$$
\tau_\prec = \tau_z \sec |\delta - \phi|
$$

(6)

under the best weather conditions.

The system noise temperature is approximately (Condon 2007)

$$
T_{\text{sys}} \approx T_{\text{rcvr}} + 5.7 \text{ K} + T_k[1 - \exp(-\tau)],
$$

(7)

where $T_{\text{rcvr}}$ is the receiver noise temperature and $T_k$ is the opacity-weighted mean kinetic temperature of the atmosphere. Current values of $T_{\text{rcvr}}$ are listed at

http://wwwlocal.gb.nrao.edu/gbtprops/man/GBTpg/GBTpg_tf.html

and air temperatures are available at

http://www.gb.nrao.edu/~rmaddale/Weather/.

If only the surface air temperature $T$ is known, then $T_k \approx T - 18 \text{ K}$ can be used to estimate $T_k$. The minimum system temperature $T_\prec$ for an observation of a source at declination $\delta$ is calculated from Equation 7 using the minimum possible opacity $\tau_\prec$ for that source.

### 3.1.2. Telescope-Surface Observing Efficiency $\eta_{\text{sur}}$

Differential solar heating during the day (defined here as the time from two hours after sunrise to three hours after sunset) deforms the GBT, producing collimation errors and deforming the primary surface of the GBT. In 2007 the measured rms surface error $\epsilon$ was $\epsilon_n \approx 0.39$ mm at night and $\epsilon_d \approx 0.46$ mm during the day (Nikolic et al. 2006, 2007). As of 2010 July, improved panel settings determined by coherent holography and incoherent out-of-focus (OOF) holography reduce can these errors to $\epsilon_n \approx 0.25$ mm and $\epsilon_d \approx 0.30$ mm. The surface aperture efficiency $\eta_A$ at wavelength $\lambda$ is given by the Ruze equation:

$$
\eta_A = \exp\left[-\left(\frac{4\pi\epsilon}{\lambda}\right)^2\right].
$$

(8)
It is \(\eta_A = 1\) for a perfect surface, regardless of the aperture illumination or blockage. Note that the radiometer equation implies that the observing efficiency is proportional to the square of the surface aperture efficiency: \(\eta_{\text{sur}} \propto \eta_A^2\). Renormalizing the observing efficiency by defining \(\eta_{\text{sur}} \equiv 1\) at night (the best thermal conditions) determines the daytime value

\[
\eta_{\text{sur}} = \exp \left[ -\frac{32\pi^2}{\lambda^2} (\epsilon_d^2 - \epsilon_n^2) \right].
\]

Inserting the new values \(\epsilon_d = 0.30\ \text{mm}\), \(\epsilon_n = 0.25\ \text{mm}\), and \(\nu = c/\lambda\) into Equation 9 yields the convenient formula

\[
\eta_{\text{sur}} = \exp \left[ -\left( \frac{\nu}{102\ \text{GHz}} \right)^2 \right]
\]
during the day for the GBT in 2010.

### 3.1.3. Tracking Efficiency \(\eta_{\text{tr}}\)

The difference between the actual beam position on the sky and the commanded position is called the tracking error. PTCS System Note 3 (Condon 2003a) and Project Note 27.2 (Condon 2003c) describe the effects of tracking errors on the sensitivity and accuracy of point-source flux measurements. Tracking errors may cause both (1) a systematic loss of signal strength that can be recovered by longer integration at the cost of reduced tracking efficiency and (2) fluctuations in measured flux density that may be neither predictable nor correctable.

Before the GBT azimuth track was replaced in 2007, the rms tracking error \(\sigma_{\text{tr}}\) was measured to be (Condon 2003b)

\[
\left( \frac{\sigma_{\text{tr}}}{\text{arcsec}} \right)^2 \approx \sigma_0^2 + \left( \frac{|v|}{2.1\ \text{m s}^{-1}} \right)^4,
\]

where \(\sigma_0\) is the rms tracking error in the limit of zero wind and \(v\) is the wind speed measured at the “Weather 2” station in Green Bank. The no-wind tracking errors \(\sigma_0\) were \(\sigma_{0n} \approx 2.8\ \text{arcsec}\) rms during the night and rose to \(\sigma_{0d} \approx 3.3\ \text{arcsec}\) during the day owing to differential solar heating (Balser et al. 2006). The actual values of both \(\sigma_{0n}\) and \(\sigma_{0d}\) are probably lower now that the azimuth track has been replaced, so these constants should be updated.

Wind increases the tracking error by exerting a force on the telescope proportional to the square of the wind speed \(|v|\). The track replacement probably did not change the effect of wind on pointing (the second term in Eq. 11).

The observing efficiency factor reflecting a Gaussian distribution of tracking errors for observations of a point source with a single beam or a sparse array of non-overlapping beams (such as the proposed K-band array of discrete feeds) relative to perfect tracking is (Condon 2007)

\[
\eta = \left[ 1 + 4 \ln(2) f^2 \right]^{-2}.
\]

The GBT tracking error is not zero even in the best conditions (nighttime with zero wind). To remain consistent with the dynamic-scheduling convention that all observing efficiencies are unity under the best conditions, we must renormalize Equation 12 to make \(\eta_{\text{tr}} = 1\) on a windless night:

\[
\eta_{\text{tr}} = \left[ \frac{1 + 4 \ln(2) f^2}{1 + 4 \ln(2) f^2} \right]^{2}.
\]
where

\[ f \equiv (\sigma_{\text{tr}} / \theta), \]  
\[ f_\prec = (\sigma_0 / \theta), \]  

and \( \theta \) is the FWHM beamwidth of the GBT at frequency \( \nu \):

\[
\left( \frac{\theta}{740 \text{ arcsec}} \right) \approx \left( \frac{\nu}{\text{GHz}} \right)^{-1}
\]  

Tracking errors made with a filled array such as MUSTANG (MUltiplexed SQUID TES Array at Ninety GHz) (http://wiki.gb.nrao.edu/bin/view/Pennarray/WebHome) are less harmful because a steady tracking offset displaces the source on the array but causes no reduction of peak flux, and a variable tracking offset reduces the peak flux but does not reduce the integrated flux. Only the integrated flux is relevant for point-source photometry, but lowering the peak flux implies a lower peak signal-to-noise ratio and hence a lower observing efficiency.

The variable (during a scan) component \( \epsilon_{\text{tr}} \) of the two-dimensional rms tracking error is smaller than the total rms tracking error \( \sigma_{\text{tr}} \). Balser et al. (2006) measured \( \epsilon_0 \approx 1''2 \) in 20 minutes for the GBT when the wind speed was very low. Wind causes tracking errors that fluctuate on time scales shorter than 20 minutes, so the fluctuating component of the GBT tracking error is

\[
\left( \frac{\epsilon_{\text{tr}}}{\text{arcsec}} \right)^2 \approx \epsilon_0^2 + \left( \frac{|v|}{2.1 \text{ m s}^{-1}} \right)^4
\]

The ratio of peak to integrated flux, or Strehl ratio \( s \), for observations made with a fluctuating tracking error having a Gaussian amplitude distribution of rms width \( \epsilon_{\text{tr}} \) is

\[ s = (1 + 4 \ln(2) f_{\nu}^2)^{-1}, \]  

where \( f_{\nu} \equiv \epsilon_{\text{tr}} / \theta \)

reflects only the fluctuating component of the tracking error. Consequently the un-normalized tracking efficiency for a filled array is equal to the square of the Strehl Ratio:

\[ \eta = s^2 = [1 + 4 \ln(2) f_{\nu}^2]^{-2}, \]  

and the normalized tracking efficiency used for dynamic scheduling is

\[ \eta_{\text{tr}} = \left[ \frac{1 + 4 \ln(2) f_{\nu}^2}{1 + 4 \ln(2) f_{\nu}^2} \right]^2, \]  

where \( f_{\nu} < = \epsilon_0 / \theta \).

To sum up, Equation 17a for observing efficiency with a filled array is the same as Equation 12a for observing efficiency with a single beam or sparse array except that the relevant zero-wind tracking error is only the fluctuating component \( \epsilon_0 \) instead of the total \( \sigma_0 \). The GBT tracking accuracy is not yet good enough for 90 GHz single-beam observations, but it is already good enough (see Equation 26) for making filled-array MUSTANG observations when the wind speed is below 8 mph \( \sim 3.6 \text{ m s}^{-1} \) (B. Mason 2010, private communication). The corresponding lowest acceptable Strehl ratio implied by Equation 17 is \( s \approx 0.7 \).
3.2. Stringency $S$

The stringency $S$ of an observation is defined as the reciprocal of the fraction of time that both the efficiency limit (Sec. 3.4.1) and tracking-error limit (Sec. 3.4.4) for a transit observation are satisfied. The more stringent an observation, the more difficult it is to schedule, so we give stringent observations higher priority by making stringency a ranking factor. The relative importance of stringency in dynamic scheduling could be adjusted by making the ranking factor an arbitrary power of $S$, but so far we have used $S$ to the first power for simplicity.

Stringency depends on observing frequency, source declination (only because the transit zenith angle depends on source declination), receiver noise, telescope performance, efficiency limits, and the long-term weather history of Green Bank. Thus the stringency calculations must be updated whenever we update the efficiencies or the efficiency limits. Balser (2007) used historical weather data from 2004 May 1 through 2007 March 1 plus current receiver and telescope performance data and efficiency limits to calculate stringency as a function of frequency at the zenith (Fig. 3) and at nonzero zenith angles (Fig. 4). For example, the zenith stringency near the $\nu \approx 22.3$ GHz water line is about 10, so the total observing time available at this frequency is less than 900 hours per year. At the maximum elevation of the Galactic Center the stringency of a water-line observation is about 33.
Fig. 3.— Zenith stringency, with contributions from atmospheric opacity alone (blue line) and from wind alone (green line). Abscissa: frequency (GHz). Ordinate: zenith stringency (dimensionless).
Fig. 4.— Stringencies for observations at elevations 25, 30, 50, 75, and 90 degrees. Abscissa: frequency (GHz). Ordinate: stringency (dimensionless).
3.3. Pressure Feedback

The schedule “pressure” $P$ is a measure of unsatisfied demand. Feedback can be used to equalize pressure across right ascension, frequency band, etc. by favoring sessions having higher pressure values. Feedback is “blind” and competes with observing efficiency, so it reduces efficiency and should be used only as a last resort. We found it necessary to apply a small amount of pressure feedback to equalize pool pressures across right ascension and observing frequency.

3.3.1. Right-ascension Pressure $P_\alpha$

Dynamic scheduling must solve a chronic problem affecting the GBT and most other telescopes: the demand for telescope time depends strongly on factors that are independent of scientific merit. In particular, LSTs near the right ascension of the Galactic Center ($\alpha \approx 18^h$) are heavily oversubscribed. Without active intervention, approved projects requesting time near $18^h$ right ascension would languish in the pool much longer than projects of equal scientific merit requesting other right ascensions.

A goal of dynamic scheduling is to keep any factors that compete with scientific merit from discriminating among approved proposals. We therefore introduced a ranking factor depending on the pool pressure $P$ to level the playing field. The overall pressure can be broken into subfactors, each of which addresses a particular problem. The most important is the subfactor reflecting the nonuniform distribution of observing projects in right ascension. We assign each session in every project a characteristic right ascension. The sessions are then divided among 24 right-ascension bins of width 1 hour. Within each hour of right ascension $\alpha$, the total number $n_\alpha$ of approved observing hours is the sum of the number already done ($d_\alpha$) and the number remaining ($r_\alpha$) in the pool:

$$n_\alpha = d_\alpha + r_\alpha.$$  

(18)

The goal of the pressure factor is to ensure that, in the long run, the fraction of approved observing hours that have not been scheduled is nearly independent of right ascension. We therefore defined the current value of the pressure in each right-ascension bin as

$$P_\alpha \equiv 1 + \ln \left( \frac{n_\alpha}{d_\alpha} \right).$$  

(19)

Pressure gradients in right ascension can be reduced by favoring sessions whose right ascensions have higher pressures. Pressure is not easily predicted by calculation, so we must use “blind” feedback to equalize it. To control the amount of pressure feedback in our actual ranking equation (Eq. 1), we introduced the right-ascension pressure feedback gain $\beta$ as an adjustable exponent: the ranking factor corresponding to $P_\alpha$ is $P^\beta_\alpha$, where $0 \leq \beta \leq 1$. Our simulations (Sec. 4.1) indicate that $\beta = 1$ quickly removes pressure gradients but noticeably lowers observing efficiency. We simulated schedules using smaller values of $\beta$ and settled on the smallest effective value $\beta \approx 0.3$. Figure 5 from a simulation shows the right-ascension distributions of proposed and dynamically scheduled observations.
Fig. 5.— For each hour of $\alpha$, the number $n_\alpha$ (top line of the histogram) of approved hours is the number done $d_\alpha$ after one year (filled bar) plus the number remaining $r_\alpha$ in the pool (empty rectangle). If all $r_\alpha/n_\alpha$ values were the same, the empty rectangles would all have the same height in this logarithmic histogram. Abscissa: session right ascension $\alpha$ (h). Ordinate: number of hours per bin (dimensionless).
3.3.2. Frequency Pressure $P_\nu$

Our simulations show that ranking by the product of efficiency and stringency favors some low frequencies over others, so that X-band and C-band sessions were scheduled “too quickly.” Both efficiency and stringency are not far from unity at low frequencies, so these ranking factors are not very effective at choosing among low-frequency sessions. We therefore introduced the frequency-dependent pressure $P_\nu$ and the feedback ranking factor $P_\nu^\gamma$. By analogy with Equations 18 and 19, within each frequency band (L, C, X, U, …) we consider the number $n_\nu$ of approved observing hours, the number $d_\nu$ already done, and the number $r_\alpha$ remaining in the pool:

$$n_\nu = d_\nu + r_\nu$$

(20)

and define the pressure in each frequency band as

$$P_\nu \equiv 1 + \ln \left( \frac{n_\nu}{d_\nu} \right).$$

(21)

Our simulations showed that the exponent value $\gamma \approx 0.5$ is needed in the ranking equation to equalize the scheduling rate across frequency bands.

Figures 6 and 7 show distributions of observing frequency throughout the year for dynamically scheduled and traditionally scheduled observations, respectively, from our simulations (Sec. 4). Figure 6 indicates that frequency-dependent feedback with $\gamma = 0.5$ is sufficient to keep the C-band and X-band observations from being scheduled too quickly at the beginning of each trimester. The most obvious difference between dynamic and traditional (Fig. 7) scheduling is that observations at frequencies near 50 GHz can be dynamically scheduled during the summer. The reasons are that the principal source of opacity is the nearly constant oxygen line (Fig. 1), not seasonal water vapor or hydrosols, and wind is a major contributor to zenith stringency (Fig. 3). Some calm and clear summer nights are good for Q-band observing in Green Bank. They are rare enough, however, that simply relaxing the prohibition of scheduling $\nu > 10$ GHz observations in the summer would not greatly increase the Q-band time that could be scheduled traditionally.
Fig. 6.— This plot shows the frequency distribution of dynamically scheduled sessions throughout the year. Abscissa: date Ordinate: frequency (GHz).
Fig. 7.— This plot shows the frequency distribution of traditionally scheduled sessions throughout the year. Abscissa: date Ordinate: frequency (GHz).
3.4. Performance Limits

Performance limits must be defined to exclude very inefficient or even unacceptable observations, of sources below the telescope elevation limits for example. A candidate observing session must satisfy all relevant performance limits; otherwise its ranking score is zero (automatic rejection) or so strongly downgraded that it will run only if nothing else is available to fill potential dead time. This section lists the performance limits associated with observing efficiency, absolute hour angle, zenith angle, tracking error, and atmospheric stability. Note that these are only default limits for dynamic scheduling, and the observer is allowed to override some of them. For example, geodetic VLBI observations often require very short projected baselines available only at zenith angles approaching the hardware limit \( z = 85^\circ \). Observations approaching the \( z = 85^\circ \) hardware limit are normally rejected by our hour-angle limit (Sec. 3.4.2) because they are so inefficient, so the observer would have to override this hour-angle limit. Of course, the observer cannot override any hardware limits. Conversely, an observer may decide that a limit is too lax. The default tracking-error limit (Sec. 3.4.4) corresponds to a 10% rms flux-density error; it would be tightened by an observer demanding 5% accuracy. In general, it is best to let the observer specify limits in terms of data quality and make the dynamic-scheduling software do the conversion from data quality to telescope performance requirements. Thus the observer could simply specify 5% photometric accuracy without having to calculate the GBT pointing errors required to attain that accuracy.

3.4.1. Observing Efficiency Limit \( l_{\text{eff}} \)

The telescope time required to reach a given SNR is inversely proportional to the observing efficiency \( \eta \), so we want to avoid scheduling inefficient observations. We began our simulations by requiring \( \eta_{\text{min}} = 0.5 \) at all frequencies on the grounds that observing time \( t \propto \eta^{-1} \) diverges rapidly when \( \eta < 0.5 \). However, the observing efficiency attainable in practice is actually a strong function of frequency and almost never falls to 0.5 at low frequencies, so we allowed \( \eta_{\text{min}} \) to vary with frequency in a way that prohibits needlessly inefficient observations at any frequency. Our simulations of observations at frequencies below 50 GHz indicate that the average efficiency \( \langle \eta \rangle \) that we must accept in order to schedule most programs depends on frequency as shown by the red points in Figure 9. The average observing efficiency can be approximated by

\[
\langle \eta \rangle \approx 0.74 + 0.155 \cos \left( \frac{\nu}{\nu_0} \right) + 0.120 \cos \left( \frac{2\nu}{\nu_0} \right) - 0.030 \cos \left( \frac{3\nu}{\nu_0} \right) - 0.010 \cos \left( \frac{4\nu}{\nu_0} \right),
\]

where \( \nu_0 = 12.8 \text{ GHz} \). Equation 22 is valid only for frequencies \( \nu \leq 50 \text{ GHz} \). The corresponding equation for 68 GHz \( \leq \nu \leq 117 \text{ GHz} \) is

\[
\langle \eta \rangle \approx 0.5 + 0.0 \cos \left( \frac{\nu - \langle \nu \rangle}{\nu_1} \right) + 0.0 \sin \left( \frac{\nu - \langle \nu \rangle}{\nu_1} \right) + 0.0 \cos \left( \frac{2\nu - \langle \nu \rangle}{\nu_1} \right) + 0.0 \sin \left( \frac{2\nu - \langle \nu \rangle}{\nu_1} \right),
\]

where \( \langle \nu \rangle = 92 \text{ GHz} \) and \( \nu_1 = 15.3 \text{ GHz} \).

We empirically set the minimum observing efficiency \( \eta_{\text{min}} \) above which there is no ranking penalty to be slightly lower than the average efficiency:

\[
\eta_{\text{min}} = \langle \eta \rangle - 0.02 - 0.1(1 - \langle \eta \rangle)
\]
to ensure that enough high-frequency observations can be scheduled. This minimum efficiency is shown by the curve in Figure 9. The ranking cutoff below $\eta_{\text{min}}$ is not infinitely sharp, so observing programs may be scheduled with efficiencies slightly lower than $\eta_{\text{min}}$ if there are no good alternatives in the pool. This minimizes “dead time” without significantly lowering the average observing efficiency.

If $\eta \geq \eta_{\text{min}}$ then $l_{\text{eff}} = 1$; else

$$
\begin{align*}
l_{\text{eff}} &= \exp \left[ -\frac{(\eta - \eta_{\text{min}})^2}{2\sigma^2} \right],
\end{align*}
$$

(24)

where $\sigma = 0.02$ is an arbitrary parameter that adjusts the width of the Gaussian cutoff taper.

If the actual observing efficiency $\eta_{\text{obs}}$ at the start of a scheduled observing session is significantly lower than $\eta_{\text{min}}$ because the actual weather is worse than the forecast weather, it may be necessary to cancel that session and replace it with a backup session. Our criterion for canceling is

$$
\eta_{\text{obs}} < \exp[-0.05 + 1.5 \ln(\eta_{\text{min}})].
$$

(24a)

### 3.4.2. Hour-angle Limit $l_{\text{HA}}$

As the absolute hour angle $|H|$ increases, the atmospheric efficiency $\eta_{\text{atm}}$ decreases, first slowly and then rapidly (Condon 2007). It is therefore quite inefficient to observe a source too far from transit. We define $\eta_{\text{HA}}$ as the observing efficiency at hour angle $H$ relative to the observing efficiency at transit. The value of $|H|$ at which $\eta_{\text{HA}}$ falls sharply depends only weakly on weather conditions, so we used “good” weather conditions (Condon 2007) to calculate the $|H|$ values at which $\eta_{\text{HA}} = (0.5\eta_{\text{min}})^{1/2}$. This limiting value of $\eta_{\text{HA}}$ is the geometric mean of 0.5, which is unnecessarily lenient at low frequencies, and $\eta_{\text{min}}$, which is unnecessarily strict at low frequencies, where $\eta_{\text{min}} > 0.9$ normally.

The hour-angle limits vary with frequency $\nu$ and source declination $\delta$ as shown in Figure 8. Note that low-frequency observations should not be scheduled at significantly higher $|H|$ than high-frequency observations, contrary to current practice. Although the atmospheric opacity is small at low frequencies, $T_{\text{sys}}$ is also small, so even a little thermal emission from a high airmass can seriously degrade efficiency.

If $\eta_{\text{HA}} \geq (0.5\eta_{\text{min}})^{1/2}$ then $l_{\text{HA}} = 1$; else $l_{\text{HA}} = 0$.

These hour-angle limits are always stricter than the hour-angle limits implied by hardware zenith-angle limit $z < 85^\circ$. They are “soft” and may be overridden by any observer willing to tolerate low observing efficiency.

### 3.4.3. Zenith-angle Limit $l_z$

The GBT hardware zenith-angle limit is $z < 85^\circ$. Thus $l_z = 1$ if $z < 85^\circ$; else $l_z = 0$.

Observers cannot increase this limit, but they should be allowed to decrease it. Note that the default hour-angle limits $l_{\text{HA}}$ should make it unnecessary for most observers to decrease the zenith-angle limit in order to avoid low observing efficiency.
Fig. 8.— Absolute hour-angle limits beyond which the observing efficiency is falling rapidly. Abscissa: frequency (GHz). Ordinate: absolute hour angle (h). Parameter: source declination $\delta$ (deg).
3.4.4. Tracking-error Limit \( l_{\text{tr}} \)

Tracking errors have different effects on single-beam/sparse-array and filled-array observations. Consequently there are two independent equations for the tracking-error limit \( l_{\text{tr}} \), one applying only to single-beam and sparse-array observations (Eq. 25) and the other only to filled-array observations (Eq. 26).

Tracking errors cause intensity-proportional flux uncertainties in single-beam and sparse-array observations. Strong winds may cause unacceptably large fractional flux errors, implying wind-speed limits for high-frequency GBT observations. If we require \( \sigma_s \lesssim 0.1 \) (10% rms flux errors) for astronomically usable performance, then the largest acceptable tracking error is (Condon 2003a)

\[
f = 0.20 = \frac{\sigma_{\text{tr}}}{\theta},
\]

where \( \sigma_{\text{tr}} \) is given by Equation 11 and \( \theta \) by Equation 14.

For single-beam and sparse-array observations: If \( f \leq 0.20 \) then \( l_{\text{tr}} = 1 \); else \( l_{\text{tr}} = 0 \).

Observers desiring better photometric accuracy should be allowed to override this default and use smaller (but not larger) tracking-error limits. The observer would specify the largest acceptable rms photometric error \( \sigma_s < 0.1 \), and the dynamic scheduling program would calculate the largest acceptable tracking error \( f \leq 0.20(\sigma_s/0.1)^{1/2} \). For example, if the observer needs 5% flux accuracy, the maximum acceptable value of \( f \) would drop from \( f = 0.2 \) to \( f = 0.141 \).

Tracking errors do not cause photometric errors (errors in integrated flux density) for point-source observations made with filled arrays such as MUSTANG, so the tracking limit above does not apply. However, the variable component of the tracking error degrades the dynamic range of images made with filled arrays by blurring the point-source response. Brian Mason (2007 private communication) originally suggested that the minimum Strehl ratio be set to \( s = 0.9 \) for “acceptable” image quality, which corresponds to a largest acceptable tracking error \( f_v \approx 0.20 \). Additional observing experience with MUSTANG led him to conclude that winds as high as 8 mph are acceptable, reducing the minimum acceptable Strehl ratio to \( s = 0.7 \) (Eq. 17) and raising the largest acceptable tracking error for filled-array observations to

\[
f_v = 0.40 = \frac{\epsilon_{\text{tr}}}{\theta},
\]

where \( \epsilon_{\text{tr}} \) is given by Equation 15 and \( \theta \) by Equation 14.

For filled-array observations: If \( f_v \leq 0.40 \) then \( l_{\text{tr}} = 1 \); else \( l_{\text{tr}} = 0 \).

Observers desiring higher dynamic ranges in their array images should be allowed to override this default and specify smaller (but not larger) tracking-error limits.

3.4.5. Atmospheric Stability Limit \( l_{\text{st}} \)

Hydrosols are water droplets in clouds. They are not well mixed in the atmosphere, so they cause short-term fluctuations in antenna temperature that are proportional to \( \nu^2 \) and can degrade single-dish continuum observations at frequencies higher than about 2 GHz. These relatively slow, broadband fluctuations have little effect on pulsar and spectral-line observations. Continuum observations at frequencies above about 2 GHz should normally be scheduled only when there are no hydrosols; that is, when the sky
is clear. We can use the forecast downward irradiance to estimate cloud cover and hence atmospheric stability, and (Balser 2010) recommends $I_{\text{down}} < 330 \text{ W m}^{-2}$ for acceptable atmospheric stability. Thus, for continuum observations above 2 GHz, $l_{\text{st}} = 1$ when $I_{\text{down}} < 330 \text{ W m}^{-2}$; else $l_{\text{st}} = 0$. For all other observations, $l_{\text{st}} = 1$ regardless of cloud cover or downward irradiance. These are defaults only, and observers should be allowed to change them at their own risk.

### 3.5. “Other” Ranking Factors $f_o = f_{\text{oos}} f_{\text{com}} f_{\text{sg}} f_{\text{tp}}$

The “other” ranking factors are needed to implement management decisions. Like feedback (Sec. 3.3), they compete with efficiency factors and potentially degrade the overall observing efficiency of the GBT. They should therefore be kept as small as possible consistent with achieving their goals. The values listed below are just first guesses, so they will have to be updated as we gain experience with dynamic scheduling on the GBT.

#### 3.5.1. Observer On Site $f_{\text{oos}}$

To encourage observer visits to Green Bank, we try to schedule visiting observers within one week of their arrival. The “observer on site” factor $f_{\text{oos}}$ allows dynamic scheduling to expedite their approved programs.

If the observer is on-site then $f_{\text{oos}} = 1.2$; else $f_{\text{oos}} = 1$.

#### 3.5.2. Project Completion $f_{\text{com}}$

To ensure timely completion of approved projects, we use the factor $f_{\text{com}}$ to favor observations by any project that has only a small fraction of its total allocated time remaining to be scheduled.

If a project is $x\%$ complete then $f_{\text{com}} = 1 + x/1000$.

#### 3.5.3. Science Grade $f_{\text{sg}}$

The GBT Scheduling Committee assigns scientific grades of A, B, or C to accepted projects. Only the best projects receive A grades. Traditionally they were given a small scheduling priority, and they remained in the pool even if they are not completed by the end of a trimester. Most approved projects receive B grades and will receive the approved telescope time. However, they are dropped from the pool at the end of the trimester, even if they have some remaining time. Projects with C grades are accepted only as “fillers” and scheduled only when no A or B projects can be executed.

If a project is graded A or B $f_{\text{sg}} = 1$; else $f_{\text{sg}} = 0.1$. 
3.5.4. Thesis Project $f_{tp}$

If a project is part of a thesis, it benefits by a small factor $f_{tp}$ intended as a tie-breaker.

If a project is part of a thesis $f_{tp} = 1.05$; else $f_{tp} = 1$.

4. Simulations

Our simulation program tests the effectiveness of dynamic scheduling based on the ranking system described in Section 3 and compares it with the traditional scheduling system using quantitative metrics. Each simulation is based on actual Green Bank weather during the 11 month period from 01 Feb 2006–31 Dec 2006. There are small gaps in the weather data so only about 10.4 months in this interval could actually be simulated. Observing programs were randomly generated with input probabilities designed to match recent proposal statistics.

4.1. Dynamic Scheduling Simulations

We assumed that each proposal or project could be broken into multiple observing sessions, where each session is defined by a unique set of criteria (e.g., hardware, LST range, etc.). For example, an approved proposal might be given four observing sessions of five hours each. Each session consists of a fixed telescope period (TP) randomly chosen to be an integer between 2 and 6 hours. A TP less than 2 hours is not very efficient owing to setup time (e.g., rotate the receiver into focus, calibration, etc.). We did not consider setup time when calculating observing efficiency, so the TP duration actually has almost no effect on the simulated observing efficiency. The upper limit of 6 hours matches the decorrelation time of the Green Bank weather, in particular the wind, based on historical data (Balser 2007). For simplicity we decided that once a TP is started, it will be allowed to finish. The number of TPs per project was determined randomly to be an integer between 1 and 5. The number of TPs per project also has almost no effect on the simulated observing efficiency.

We randomly generated observing sessions for each trimester: A (February–May), B (June–September), and C (October–January). One full year is 8760 hr. To this observing pool of new sessions we added an initial backlog of one month (720 hr) for a total of 9390 hr. Given a mean TP of 4 hours and a mean number of sessions of 3, the average project length was 12 hr. Therefore, we randomly generated about 783 independent projects.

The simulated distribution of frequency bands (L, S, C, X, U, K, Ka, and Q) was initially matched to the statistics of proposals recently submitted to the GBT. For our simulations, we included in L band all frequencies below 2 GHz. Also, we used historical data to place 40% of the K-band sessions at the water line frequency of 22.3 GHz. We quickly found that the Green Bank weather is not good enough to satisfy recent high-frequency proposal pressure. We therefore adjusted the annual distribution of observing frequencies in our simulations to maximize the possible number of approved high-frequency projects consistent with the weather conditions at Green Bank: about 45% of the observing time is at L-band or lower frequencies, 5% S-band, 10% C-band, 5% X-band, 5% Ku-band, 10% K-band, 10% Ka-band, and 10% Q-band. Within the year, we adjusted the seasonal distribution of frequency bands
to match seasonal weather variations. For example, few K-band observations can be scheduled during the summer (trimester B).

Note that traditional GBT scheduling has always made similar adjustments. The human telescope scheduler (Carl Bignell) estimated the number of high-frequency hours that could be reasonably be scheduled in trimesters A and C, and the GBT Scheduling Committee approved only that many hours. Consequently, many rejected high-frequency proposals had higher referee’s rankings than many accepted low-frequency proposals. No high-frequency proposals were accepted for traditional scheduling during the summer trimester B.

Compared with traditional scheduling, dynamic scheduling brings three advantages: (1) We can tune the simulations to yield the optimum distributions of observing frequencies that the GBT Scheduling Committee should consider when approving proposals each trimester. (2) Some high-frequency (especially U and Q band) observations can be dynamically scheduled during the summer trimester. (3) More high-frequency observations can be scheduled in all trimesters.

The sky distribution of the simulated observations also reflects historical demand. About 75% of the observations were focused on a specific source or region of the sky and 25% were all-sky. Of the single-source sessions, 1/3 were in the Galactic Plane and 2/3 were extragalactic. About 80% of the time in the Galactic Plane was distributed randomly in the longitude range $0^\circ < l < 250^\circ$ visible to the GBT, and 20% were placed at the Galactic Center. The extragalactic and all-sky observations were randomly distributed over the sky north of $-35^\circ$ declination.

We assumed that 25% of the observations below 10 GHz were available to be used as backups. By “backups” we mean observing sessions that can be executed from scripts by the telescope operator without notifying the observer, plus sessions for which the observers have volunteered to be “on call” at any time. These low-frequency backups are needed to fill unexpected gaps in the telescope schedule—in our simulations, some scheduled high-frequency projects had to be aborted because the actual observing weather was much worse than the forecast weather.

The simulations started at the beginning of the first trimester (01 February 2006, 00:00:00 EST). All sessions in the pool at that time (the backlog plus all projects proposed for trimester A) were ranked using Equation 1. Proposals for trimesters B and C were added to the observing pool when those trimesters began in June and October, respectively. For the simulations we set the atmospheric stability limit ($l_{st}$) and the “other” factors to unity.

We use the 2006 CLEO weather forecasts stored at
http://www.gb.nrao.edu/~rmaddale/Weather/index.html
The forecast wind speed is not very well correlated with the observed wind speed from Weather Station 2. Therefore, to ensure that the actual wind speed is equal to or lower than the predicted wind speed most of the time, we fit a polynomial curve to the 80$^{th}$ percentile of data points in a scatter plot of the measured versus forecast wind speed. This was done separately for day and night. This polynomial equation was used to correct the forecast wind speed to make a realistic match to the Weather 2 data upon which the tracking-error equations are based.

The simulation program calculated the rank for each session based on the 24–36 hour (or 48–60 hour) forecast. The highest-ranked session was scheduled if the weather had not significantly deteriorated by the observing time; that is, the “actual” observing efficiency had to be greater than $\eta_{\text{min}} - 0.1$ and the
tracking-error limit, $l_{\text{tr}}$, had to be 1. The 0–12 hour forecast for-opacity and the current wind speed from Weather Station 2 were used to calculate the “actual” observing efficiency and tracking error. If the actual weather was not good enough for the originally scheduled session, the highest-ranked (for the actual weather conditions) backup session was selected. This observing time was called backup time. If there was no acceptable backup session, then the telescope did nothing; this time was called dead time. If the wind speed exceeded the maximum allowed wind speed (11.1 m/s) for GBT operation, then the telescope was stowed. This time was called stowed time. The number of stowed hours per year is negligible, typically $\sim 10$.

4.2. Traditional Scheduling Simulations

Traditional GBT scheduling (See http://wiki.gb.nrao.edu/bin/view/Observing/GbtSchedulerProcs) pairs two projects, one at a high frequency (usually above 10 GHz) and the other at a low frequency (usually below 10 GHz). A pair of sessions separated by about two days is set aside for the two projects. The high-frequency observer decides which session to take based on the weather forecast between 5–29 hours in advance of the first session. The low-frequency observer gets the other day. This scheme is only used from October through May. During the summer months June through September only low-frequency sessions are selected.

We simulated traditional scheduling as follows. Sessions were created using the same “seed” in the random-number generator that was used in the corresponding dynamic-scheduling simulation. Each simulation started at the beginning of the first trimester (01 February 2006, 00:00:00 EST). Proposals from the second and third trimesters were added to the pool at the appropriate dates. No high-frequency observations were scheduled during trimester B. During trimesters A and C, a high frequency (> 10 GHz) session and a low frequency (< 10 GHz) session were randomly selected from the available sessions (backlog plus proposals for the first trimester). The high-frequency session was chosen if $\eta > 0.5$ and $l_{\text{tr}} = 1$ in the 24–36 hr (or 48–60 hr) forecast; otherwise, the low-frequency session was scheduled. The next TP was given to the project not scheduled if possible; if not, then the telescope was left idle (dead time). As in the dynamic scheduling simulation, if the wind speed exceeded the shutdown limit then the telescope was stowed.

5. Results

The main benefit of dynamic scheduling is increased observing efficiency, especially at high frequencies. Dynamic scheduling with 24-hour (48-hour) notice reduced the number of backup hours scheduled from 1803 to 499 (572) and the number of dead hours from 129 to 13 (63). The best metric for comparing dynamic and traditional schedules is the “effective” observing time $t_{\text{eff}}$ per year scheduled in each frequency band. The effective observing time is simply clock time multiplied by observing efficiency, and it equals the clock time for observations perfectly scheduled under the best possible conditions. Figure 9 shows the distribution of observing efficiencies for dynamically scheduled sessions with 24-hour notice as a function of frequency, and Figure 10 is the corresponding plot for traditional scheduling.
Fig. 9.— This plot shows the average observing efficiency $\langle \eta \rangle$ (filled circles with error bars), the minimum observing efficiency $\eta_{\text{min}}$ (curve), and the actual observing efficiencies (data points) attained by sessions dynamically scheduled 24–36 hours ahead. Abscissa: frequency (GHz). Ordinate: observing efficiency $\eta$. 

mode:1 (a,b,g,s): 1.00 0.30 0.50 0.02  Forecast: 2006 24-35hr
Fig. 10.— Data points in this plot indicate the actual observing efficiencies attained with the old scheduling system. Abscissa: frequency (GHz). Ordinate: observing efficiency $\eta$. 

mode:3 (a,b,g,s): 1.00 0.30 0.50 0.02  Forecast: 2006 24-35hr
Some fraction of observing sessions dynamically scheduled on the basis of forecast weather must be canceled at the last minute in favor of more robust backup programs because the actual weather is much worse than forecast. The probability of cancellation is shown as a function of frequency band in Figure 11 for dynamic scheduling with 24-hour minimum notice and in Figure 12 for scheduling with 48-hour minimum notice. This “disappointment rate” is about 20% at K-band (18–26 GHz), where the opacity of the weather-sensitive water-vapor line is greatest. It averages about 15% at higher frequencies where hydrosols and wind are more important. Low-frequency programs are rarely canceled. The disappointment rate is slightly higher but still acceptable for schedules based on 48–60 hour forecasts.

The effective numbers of hours per year of dynamic and traditional scheduling are listed in Table 1 (24 hours notice) and Table 2 (48 hours notice) below. The columns of Tables 1 and 2 list:

1. Frequency Band
2. Percentages of approved time for each band
3. Clock hours dynamically scheduled in each band during the 10.4-month simulation.
4. Clock hours traditionally scheduled in each band during the 10.4-month simulation.
5. Effective hours dynamically scheduled in each band during the 10.4-month simulation.
6. Effective hours traditionally scheduled in each band during the 10.4-month simulation.
7. Ratio $D/T$ of effective hours dynamically scheduled to effective hours traditionally scheduled in each band.

Note the large ratios of effective hours scheduled dynamically versus effective hours scheduled traditionally at the highest frequencies (K, Ka, and Q bands). For all high-frequency ($\nu > 10$ GHz) observations, this ratio is about 1.5. Scheduling 48–60 hours in advance is nearly as efficient and reliable as scheduling 24–36 hours in advance. This suggests that not all schedules need be made only 24–36 hours in advance. For example, observers could be given a minimum 24 hours notice on normal work days and 48 hours on weekends and holidays. Almost no K-band observing sessions are scheduled during the summer, so another option would be to give 48-hour minimum notice throughout the summer trimester B.

We did not simulate scheduling the 90 GHz MUSTANG array. Figure 2 shows that hydrosol and water-vapor continuum are the main sources of opacity at 90 GHz. The hydrosol contribution is negligible when the sky is clear, and the water-vapor continuum opacity is directly proportional to the amount of precipitable water vapor. Thus clear and moderately dry (e.g., $\leq 0.5$ cm pwv) weather is needed. Section 3.1.3 indicates that filled-array observations at 90 GHz can be made when the wind speed is less than 2.2 m s$^{-1}$. These requirements are similar to those for single feeds at the high end of Q-band (45 to 50 GHz), so we anticipate that up to several hundred hours per year of MUSTANG observations could be scheduled dynamically.

Acknowledgements: We thank Ron Maddalena for providing the CLEO weather database used in all of our simulations. Richard Prestage made helpful suggestions that improved this project note.
Fig. 11.—This plot shows for each frequency band the probability that a session scheduled 24–36 hours in advance must be canceled at the last minute and replaced by a low-frequency backup. About 15% of all high-frequency ($\nu > 10$ GHz) sessions must be canceled. Abscissa: frequency band. Ordinate: fraction of sessions canceled.
Fig. 12.— This plot shows for each frequency band the probability that a session scheduled 48–60 hours in advance must be canceled at the last minute and replaced by a low-frequency backup. Abscissa: frequency band. Ordinate: fraction of sessions canceled.
Table 1. Hours scheduled dynamically (24 hour minimum notice) and traditionally

<table>
<thead>
<tr>
<th>Frequency band</th>
<th>Approved %</th>
<th>Dynamic clock hours</th>
<th>Traditional clock hours</th>
<th>Dynamic effective hours</th>
<th>Traditional effective hours</th>
<th>D/T ratio</th>
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<tbody>
<tr>
<td>L</td>
<td>43.2</td>
<td>3140</td>
<td>3337</td>
<td>3057.7</td>
<td>3262.8</td>
<td>0.94</td>
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<td>S</td>
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<td>530</td>
<td>586</td>
<td>510.8</td>
<td>564.9</td>
<td>0.90</td>
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<tr>
<td>C</td>
<td>10.3</td>
<td>869</td>
<td>801</td>
<td>825.8</td>
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<td>330.4</td>
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<tr>
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<td>6464.3</td>
<td>6016.9</td>
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Dead 13 129  
Stow 9 3  
Total 7478 7476

Table 2. Hours scheduled dynamically (48 hour minimum notice) and traditionally

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<th>Approved %</th>
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<th>Dynamic effective hours</th>
<th>Traditional effective hours</th>
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Stow 9 3  
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Table 3. Dictionary of Variables

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REFERENCES

Balser, Dana S. 2007, “Weather Characterization and Stringency for the GBT,” DS/PN001.2


Condon, J. J. 2003c, “Refined Scientific Requirements for the PTCS,” PTCS/PN/27.2


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