A Sensitivity Calculator for the GBT

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1   Introduction – Why A New Calculator and Its Scope

The goal of this memo is to outline the requirements, information needed, and logic flow of a replacement sensitivity calculator for the GBT. The goal of the calculator is to provide observers and staff an easy way to determine the time needed to complete a proposed project or the expected sensitivity achieved by a project of a given length.

Currently, we estimate that 25% of the users of the GBT are getting their time estimates wrong by a factor of two or more even when they use our existing calculators.   Since there seems to be no patterns to the reasons for the bad estimates, we have found no easy fix and have imposed a policy that staff will check time estimates for all proposals.   To compound the problem, the technical justification sections of proposals almost always contain insufficient information for judging time estimates.   Staff very often has to 'read between the lines' or email proposers to determine the observers' actual intent. When a staff member disagrees significantly with a proposed estimate, a second staff member is involved. Thus, observers and staff expend a fair amount of time and frustration that we believe could be reduced with a replacement sensitivity calculator.

In comparison to the existing calculator, the replacement will be significantly more sophisticated since it will lead users through the complex web of decisions and choices astronomers make as they think out their sensitivity estimates.   With a well-designed calculator, observers, as they write their proposals, will have a better feel for how their choices will affect the time required or the sensitivity achieved. The new calculator will embed calculations that the current tools assume users are making with pen and pencil. As a side benefit, the proposed calculator should reduce the frustrations and learning curve for those new to radio astronomy or new to the particulars of the GBT's hardware. The new calculator will report its results in a uniform and complete way so that observers can simply copy the results into their proposal. Because of the consistent look and completeness of the output of the proposed calculator, members of the Proposal Selection Committee (PSC), and those staff members who either provide technical reviews or who schedule the telescope, will no longer have to read between the lines to ascertain whether a proposal has asked for too much or too little time to obtain the desired scientific results.

In order to generate estimates of the time needed or sensitivity achieved, the calculator will ask the user a set of questions regarding their desired hardware setup and source properties. Because different observations require different information, one goal of the memo is to give the flow of questions that should be asked of a user for various types of observing. This memo currently covers 'traditional' spectral line and continuum observing. I suggest that appendices be added that cover polarization, pulsar, etc observing modes as well as observing with the specialized hardware of Spigot, Guppi,

Zpectrometer, the planned array receivers, etc.   I will not discuss how the calculator interfaces with the Proposal Submission Tool (PST), though there is significant redundancy in the information needed by the PST and by the calculator and a heavy reliance of the inputs to the PST on the output of the calculator.

Because of the wide range of questions asked by the calculator, it can easily supply information that isn't explicitly tied to sensitivity or time estimates but that would be useful to prospective observers when planning their observations. The memo will outline what ancillary quantities might be produced by the calculator.

The calculator will limit itself to estimating the sensitivity or time for a single observation within an observing session or project.   It is up to the user on how best to derive from the calculator's output the total time for their sessions and project. Thus, we expect those writing proposals will continue to use the technical justification section of their proposals to describe how the results of the calculator were used to derive the time estimate for their projects.   Users may need to include in their technical justifications as many output logs from the calculator as they feel are needed.

Internally, the calculator will need information from the support staff about the hardware of the GBT (e.g., receiver temperatures) and weather statistics. Since the hardware information will need to be adjusted often -- when hardware is added, removed from service, or upgraded -- we need an infrastructure that gives the domain experts (engineering or scientific staff) the ability to update information without involving our programming staff in maintaining the calculator. As an example infrastructure for reducing costs, I will use the model in Toney Minter's memo "PST Requirements for GBT Resources" (see http://www.gb.nrao.edu/~tminter/PST/GBT-resources-specification-v3.pdf and http://www.gb.nrao.edu/~tminter/PST/GBT-Resources-Table.pdf) since it is the only proposed, well-formulated, and well-developed plan of how to accomplish this feat.

There are many ways in which a successful calculator can be designed. The approach taken here attempts to satisfy 95% or so of 'traditional' spectral line and continuum observations. I've tried to organize the flow of the calculator to minimize the number of questions asked. I've tried to minimize the internal information the calculator must store. The proposed methods, algorithms, and shortcuts are not being guaranteed to produce results to better than 10% in sensitivity or 20% in time. I will note those aspects of the calculator which are add-ons that might be put off to after the initial release.

Section 2 provides the general flow of questions asked of the user and outlines the results presented back to the user. To keep the discussion in §2 flowing, I have deferred the details of the calculations used in that section to §3. Section 4 outlines various sub-calculators and planning assistants which should or can be associated with the calculator. Finally, §5 lists the internal information that will be provided and maintained by the support staff.

2   Calculator Design and Questions Asked of the User

The proposed calculator will have the following general policies and look-and-feel:

- The calculator's design will be broken into subsections (frames or tabs, for example) where each section is devoted to a particular aspect of the proposed observation. Such a layout will guide the user. Because of the complexity of the calculator, it is acceptable for the deployment to be done in stages, maybe along the lines implied by the subsections.
- To make the interface more pleasant and self explanatory, the questions asked of the user will be organized by topic, rather than by how that information is used by the calculator.
- The choice of possible answers at any moment will depend upon the answers the user has given to previous questions. For example, no need to supply frequency switching as a possible observing mode for hardware that cannot accommodate that mode..
- Likewise, in various steps, the calculator can skip asking a question if the answer is already dictated by the answers the user has provided to previous questions. In these cases, the output should indicate what the assumed answer would be. For example, If Zpectrometer is the selected backend, the user won't be asked for a bandpass but the calculator's output should state that the assumed bandpass will be 14 MHz.
- At startup, the calculator will try to present default values, as outlined below.
- The calculator will try to check for error and consistency as a user enters information and answers questions.
- As the user works through the questions, he or she may choose to go back and change a previous answer. The revised answer could render some or all subsequent answers as invalid. The calculator should detect whenever someone has revised the answer to a previous questions, check whether the subsequent answers are still legal, and, if not, issue a warning and indicate through some means which answers are now illegal (e.g. by rolling up the questions to the point of the last legitimate answer and indicate which answers are now illegal). The user will then need to reconsider the now illegal answers.
- Warning and error messages should be obvious but not obtrusive.
- The calculator should be able to automatically update its results as the user modifies input values.
- If real-time error checking is not possible or practical, maybe due to poor performance, the calculator can resort to having a command the users would invoke whenever they want to verify the answers they have provided.
- Likewise, if it is not practical to provide updates to results as users input values, the calculator can resort to a command that users would invoke whenever they want to see updated results.
- The calculator will interact with sub-calculators and tools that will help the user through planning some subsets of observing types. When first initialized, a tool/sub-calculator will pick up values from the main calculator. Once the user has finished using a tool/sub-calculator it may alter values in the main calculator.
- The results of the calculator will be shown as text whose contents can either be saved to disk as an ASCII file, or other appropriate format, or placed onto the computer's clipboard. This will facilitate copying results into proposals, emails, etc.
- We may want to anticipate that the format of the calculator may become too cumbersome for those who become experienced with it. If after prototype testing we deem this worry is

warranted, then one of the allowed output file formats should be human readable so that a user can modify the output file using a standard text editor.   We will then need to add to the calculator a facility for reloading a saved and modified file. The calculator will then use the modified file as if the user had entered answers into the interface directly.

The calculators various subsections will be divided into the following categories, each of which will ask the user various questions:

A.   *General Information*

The user will first specify some overarching aspects of what they want the calculator to do.

1. User must be allowed to select whether they want the calculator to:
    a. Take a user-supplied total time for an observation and estimate a sensitivity, or
    b. Take a user-supplied sensitivity and estimate the total time (Default).
2. In either case, the user must select their units for sensitivity. The calculator, for simplicity, will allow only
    a. S (in Jy, 10^{-26} Watts m^2 Hz^{-1}, and as if measured from above the Earth's atmosphere)
    b. T_A (In K, and as measured below the Earth's atmosphere)
    c. T_R* (In K, and as if measured from above the Earth's atmosphere – Default.
3. If the user specifies they want to enter a time, the calculator will present a field into which they will enter their time estimate in seconds.
4. Or, if the user specifies they want to enter sensitivity, the calculator will present a field into which they will enter their sensitivity in their chosen units.

B.   *Hardware Information*

The users will be asked questions concerning their choice of hardware and the calculator will check the user's answers to make sure that they can be accommodated by the hardware.   Only those questions needed for the sensitivity calculator will be asked. These questions have the very useful byproduct of increasing the chance the desired experiment can be performed by the hardware, thereby reducing the frustrations of someone proposing what will eventually be deemed undoable and will further facilitate staff and PSC in their reviews of a proposal.

2.B.1   Questions

I am assuming the question asked will follow the model in Toney's memo, unless we decide to implement a different infrastructure.   As described in the memo, the questions and possible answers in each step will depend upon the answers provided in previous steps. Full listings of the hardware and modes available can be found in the GBT proposer's guide (http://www.gb.nrao.edu/gbtprops/man/GBTpg.pdf) Toney's suggested order of questions is:

1. User selects a backends from a list. No default. Note how Toney models devices like Mustang as if it were a backend that can be used with a single receiver.
2. User selects a backend mode from a list that depends upon the answer to the previous question. No question asked if the backend has only one mode. No default.

3.   User selects a receiver from a list of receivers that work with the backend and mode. No question asked if only one receiver would work. No default.

4.   If the chosen receiver is capable of dual beam observing, the user will be asked whether they will be observing with dual (default) or single beams. If the chosen receiver is incapable of dual beam observing, the calculator will assume single-beam.

5.   If the chosen receiver is capable of dual polarizations, the user will be asked whether they will be observing with full Stokes, dual (default), or single polarizations. Some receivers, like Ka and Mustang, will have only one possible polarization choice and the calculator should report what it's assuming. For example, if the chosen receiver is incapable of dual polarizations, the calculator will assume and report the use of single-polarization.

6.   User selects a bandpass width from a list of widths that are possible given the above answers. No question asked if only one width is possible. No default.

7.   Select the number of spectral windows to be used, but only if the bandwidth, backend mode, receiver, and bandpass choice allows more than one spectral window. Default = 1.

8.   Toney's 'Step 8' (minimum integration time) is strictly not needed but could be included if there's effort available. Again, the list of possible minimum times can sometimes be discerned from the answers to the previous questions.

9.   User selects a switching mode from a list of modes that are possible given the answers to the above questions. No default. The list in Toney's memo overlooked the choice between 'in-band' and 'out-of-band' frequency switching, an important difference for the sensitivity calculation. I suggest removing Toney's FSW notation and replacing with the two additional choices of IFSW and OFSW (for in- and out-of-band, respectively).

2.B.2   Calculations/Results

- After question 5, and if the mode is spectral-line, the calculator can show the minimum topocentric frequency resolution the backend can provide (see §3.H.2).

C.   *Representative Source Information*

Since projects usually observe multiple sources, the user may want to run the calculator for each. But, we should also instruct users that they can run the calculator for a representative source, or a representative set of source parameters. If the latter approach is taken, the users will need to infer how that calculation for a single or representative source translates into the time or sensitivity requirements for the body of their sources.

2.C.1   Questions

1.   Representative source Declination (Default = the latitude of Green Bank).   The calculator may display the maximum elevation this source can achieve (as well as minimum elevation for circumpolar sources).

2.   If the selected backend mode is spectral line:
     a.   The user will be asked if the observing frequencies will be given in the line's rest frame or in the topocentric frame. Default is "Rest Frame"

b. If the user has selected "Rest Frame," the calculator will need to estimate the user's topocentric frequency and minimum velocity resolution. To do so, the calculator will ask for:

    i. The rest frequency in MHz. Default is the middle of a receiver's band, as retrieved via the infrastructure outlined in Toney's memo.

    ii. Whether the user will want the calculator to use the optical, radio, redshift, or relativistic Doppler correction. Default is "optical"

    iii. If anything but "redshift" is selected, the user will be asked to enter a representative source velocity in km s^{-1}. If "redshift" is selected, the user will be asked for a source redshift z. Default in either case is 0.

c. If the user has selected topocentric, the calculator will ask for the topocentric frequency in MHz. Default is the middle of a receiver's band.

3. If the selected backend mode is "continuum", the calculator will ask for the topocentric frequency in MHz. Default is the middle of a receiver's band.

4. The user will be asked for a representative angular diameter for their source, θ_{Source}. To reduce the need for the user to enter values unnecessarily, the user will not be asked for a source size directly but will be offered a widget such as a slider with about 6 possible values. So, instead of specifying a source size, users pick the size displayed by the widget that best matches their object. The tool will have:

a. A lower limit of 0.4·FWHM, under which the object can be considered a point source for the calculator's purpose (Default).

b. An upper limit of 2·FWHM, above which the source's extent plays no further purpose in calculating estimates for sensitivity or time.

c. Step sizes that correspond to approximately 5% changes in $f(\theta_{Source})$ (see §3.F.4).

d. Units will be arc minutes.

5. The calculator will have something like a checkbox that will ask whether or not the calculator should use a model of the galactic continuum in its estimate of T_{Sys}. The default is "Yes". If "Yes", the calculator will ask for a representative J2000 Right Ascension and Declination of the source. No Defaults.

6. The user will be able to specify the representative continuum level of the source. This continuum value will be used to augment T_{Sys}. The user will be given the choice of entering this background level in either units of S or $T_R{}^*$. Default is 0.

2.C.2 Calculations/Results

- After question 2 of §2.C.1, the calculator should warn if the entered Declination does not achieve the desired minimum elevation suggested by the DSS simulations for the chosen receiver and frequency. (Declination must be > -51.57° + minimum elevation).

- After question 2 of §2.C.1, the calculator may display the number of hours the source will be above the minimum elevation. (See the CLEO timeToSet function as an example of how to perform this calculation).

- After question 3.b of §2.C.1, the calculator will display the topocentric frequency as well as the velocity resolution that corresponds to the frequency resolution from §2.B.2 (see §3.H.2).

- After question 3 or 4 of §2.C.1, the calculator should warn the user if the topocentric frequency is beyond the recommended frequency range of the receiver chosen in §2.B.1.
- After question 3 or 4 of §2.C.1, the calculator can use the information about the receiver's illumination radius to estimate and display the FWHM beam size for the topocentric frequency (see §3.H.1).
- If the user has selected anything but a "Point Source" in question 5 of §2.C.1, the calculator will issue a warning that the results will be rough.
- After question 5 of §2.C.1, the calculator can use the specified source size and the internal information on the receiver's illumination radius to provide an estimate of the telescope's efficiency (see §3.H.1).

D. Representative Weather Conditions

In order to help users through the process of making decisions concerning their proposed observations, the calculator will maintain internally various weather statistics from DSS weather simulations. Details are provided in §3F and §5.

2.D.1 Questions
1. Since weather varies throughout the year, and proposals are executed on a trimester basis, the calculator will ask the user for the trimester over which the observations are to be considered. The choices will be A (Feb 1 – May 31), B (Jun 1 – Sept 30), C (Oct 1 – Jan 31), and "All Year". The default will be the upcoming trimester.

2.D.2 Calculations/Results
- As §3F describes, from the internal weather statistics, the specified background continuum level, frequency, receiver, the expected source elevations, and an internally-generated estimate for T_{Atm}, , the calculator can determine and display representative values for
  - $<e^{\tau \cdot AirMass}>$,
  - $<Air Mass>$,
  - $<T_{Sys}>$,
  - $<EST_{TS}/EST_0>^2$, which is, the extra time needed to accomplish the observations under less than ideal weather conditions.
- From the internal wind criteria (see §5), the calculator will display:
  - The expected typical wind speeds they will encounter that don't exceed this maximum.
  - The pointing and calibration uncertainty that will arise from the expected typical wind speeds (see, for example, §3.1.3 of Condon and Balser, "Dynamic Scheduling Algorithms, Metrics, and Simulations" http://wiki.gb.nrao.edu/pub/Dynamic/DynamicProjectNotes/dspn5.2).
- From the internal values for weather stringency as a function of frequency (see §5), the calculator should display the number of hours that opacities and winds will be better than the defaults for the user's choice of trimester.   It's not critical for the calculator to display separately the number of hours that opacities or winds will be less than these values for the selected trimester.

E. *Observing and Data Reduction Details*

Observers have a number of choices in how they collect and reduce their data that significantly affect the time they will need for an experiment and the corresponding sensitivity they will achieve.   Only the most common methods will be covered by the calculator.

2.E.1   Questions

1. Data Acquisition
    a. If the user has selected any switching mode other than Toney's designation of TP, then the user will be asked for the ratio of the time they will spend on their signal (on-source or on-frequency) observation to their reference observation (R_{SigRef}). Default = 1.
    b. For Spectrometer observations (and maybe other future backends), the user will be asked whether they plan to use two or more spectral windows centered (or nearly so), on the same frequency ($N_{Overlap}$).   If possible, the calculator may suggest that this is a fantastic but seldom exploited way to increase sensitivity. The calculator should not ask this question if it can ascertain that the user has selected a hardware configuration where there are no unused Spectrometer samplers.
2. Data Reduction
    a. The user will be asked whether they plan on averaging orthogonal polarizations. Whether the user will be given this choice depends upon the user's selected hardware and the internal database of what is or isn't possible. The default, when applicable, will be "Yes".
    b. Whether they plan on difference signal and reference observations. The default is "Yes".
    c. For spectral-line projects, the user will be asked whether they plan on smoothing their on-source and off-source data. If they answer, "Yes", they will then be asked to provide:
        i. Whether they will be smoothing to a specified:
            1. Velocity resolution in km s^{-1} in the source's rest frame (Default), or
            2. Frequency resolution in MHz in the topocentric frame, or
            3. Frequency resolution in MHz in the rest frame.
        ii. The value they will use in smoothing their on-source data (BW, Default = the minimum frequency resolution the hardware setup provides).
        iii. The value they will use in smoothing their off-source data (BW_{Ref}, Default = the minimum frequency resolution the hardware setup provides).
    d. The user will be asked the number references (off) positions they will average together and use for differencing with each on-source (signal) observation ($N_{AvrgRef}$, Default=1).

2.E.2   Calculations/Results

- From question 2.c of 2.E.1, the calculator will display the topocentric frequency resolution (BW, see §3.H.2).
- Using the equations of §3:

- t_{Sig}, t_{Ref}, t_{eff}. Both t_{Sig} and t_{Ref} will be checked against the possible minimum values for the current hardware setup and a warning message issued if either of these are below that minimum.
        - R_{SigRef} and $N_{RefSmthAvrg}$
        - K_1, K_2, and N_{Samp}^{Uncorr}
        - Confusion limit and any messages regarding 1/F.
- Any output information generated by the sub-calculators or assistants.
- Finally, either the calculated:
        - t_{Total} (if the user has requested to convert a sensitivity into an observing time), or
        - sensitivity in the user's requested units (if the user has requested to convert a total time into sensitivity) .

3   Equations and Terms

In order to appreciate the questions the calculator will ask or the information it needs to store internally, I will present the various equations and quantities used to convert from sensitivity to observing time as well as the inverse, from time to sensitivity. We know from experience and observers requests that the calculator must have these two modes.

A.   Definitions and Terms

Throughout I will use the following definitions:

AirMass = a representative air mass through which the observations will be made.

BW = bandwidth in MHz, either native to the backend or the bandwidth to which the user is expecting to smooth to.

BW_{Ref} = bandwidth in MHz that the reference (off) observation will be smoothed to.

DishRadius = illumination radius for the selected receiver in m. Can be < 50 m.

$Distance_{Ref}$ = angular distance between a signal (on) and reference (off) position.

D_{Mpc} = distance to a galaxy in Mpc.

El_{Min}, El_{Max} = range in observing elevation. El_{Max} = Source Declination + 51.57°.

EST = the effective Integration time ($T_{sys} \cdot e^{\tau \cdot AirMass}$) which is proportional to the signal-to-noise in an observation when there are no winds or surface errors.

EST_0 = the effective Integration time under the best possible weather conditions.

EST_{TS} = the effective Integration time but fudged by the expect loss in efficiency due to tracking and surface errors.

Δv = velocity resolution in km s^{-1}.

f_$v_{Oversample}$ and f_$h_{Oversample}$ = oversampling in the V and H directions when mapping. Values > 1 indicate oversampling).

Frequency = topocentric frequency in MHz

η = an efficiency which takes into consideration surface errors as a function of frequency and maybe elevation as well as the user's source size (see §3F).

η_0 = the aperture efficiency at long wavelengths and receiver and frequency dependent.

η_A = the aperture efficiency which takes into consideration surface errors as a function of frequency and maybe elevation (see §3F).

η_{Dss} = the normalized observing efficiency, in units of time, as suggested by DSS simulations and the product $\eta_{Track}\,\eta_{Surf}\,\eta_{Atm}$.

η_{Track}, η_{Surf}, η_{Atm} = the normalized observing efficiency, in units of time, as suggested by DSS simulations due to tracking errors (e.g., wind induced), thermal-induced surface errors, and atmospheric conditions.

n_{Off} = number of on (signal) observations or OTF strips in a map before performing an off (reference) observation.

θ_{Source} = Source size in arc minutes.

k = Boltzmann's constant.

K_1 = sampling sensitivity of a backend and, thus, is hardware dependent.

K_2 = autocorrelation channel weighting factor for spectral line backends or a measure of the independence of samples for continuum observing; hence hardware dependent.

$N_{AvrgRef}$ = number of references observations that will be averaged together in the data reduction and used for every signal (on) observation.

N_{Line}, N_{Window} = number of lines in the spectral assistant and the number of spectral windows that will be used to cover those lines.

$N_{Overlap}$ = number of samplers that are observing the same frequency, beam, and polarization.

$N_{RefSmthAvrg}$ = amount by which a reference observation is smoothed or the number of reference observations that are averaged together.

N_{Samp} = number of samplers in the backend whose data will be averaged together.

N_{Samp}^{Uncorr} = degree to which backend samplers are measuring uncorrelated information.   For example, = 2 when averaging orthogonal polarizations and when using either in-band frequency switching or nodding.

N_V, N_H = number of samples in the V and H direction in a map

R_{SigRef} = ratio of time spent on the signal observation to the time on the reference observation.

σ_S = user-specified desired sensitivity in units of Jy (above atmosphere).

$\sigma_{T_R^*}$ = user-specified desired sensitivity in K in the T_R^* (above atmosphere) temperature scale.

σ_{T_A} = desired sensitivity in K in the T_A (below atmosphere) temperature scale.

$\sigma_{M_{HI}}$ = desired sensitivity in HI in units of solar masses.

τ = a representative zenith atmospheric opacity in units of Nepers.

τ_0 = the best possible zenith atmospheric opacity in units of Nepers.

T_{Sys} = expected approximate system temperature in K at a representative elevation.

t_{eff} = effective Integration time in seconds, essentially the time that satisfies the radiometer equation and is related to the actual observing time in different ways, depending upon the observing mode.

t_{Sig} = time spent in seconds on a source or signal position or frequency.

t_{Ref} = time spent in seconds on a reference position or frequency.

t_{Total} = total time in seconds needed to complete an observation.

t_{Pixel} = time spent on each pixel in a map.

$t_{MapMove}$ = time to move from pixel to pixel or row-to-row in a map

$t_{RefMove}$ = time to move to the reference (off) position

t_{Column}, t_{Row} = time to complete a column or row in an OTF map.

T_{Atm} = the temperature of the atmosphere in K to use in an estimate of T_{Sys}, approximately the temperature of the atmospheric layer that is contributing most to the opacity.

T_{CMB} = the cosmic microwave background = 2.7 K.

$T_{BG}{}^{Gal}$ = the temperature in K of the galactic background in the direction of the observation.

T_{BG} = the continuum temperature in K of the user's source.

T_{Spill} = the contribution to T_{Sys} in K from spillover ≈ 3 K.

T_{Rcvrl} = the contribution to T_{Sys} in K from the receiver.

v, H, h = extent of a map in arcmin. H = h/cos(v).

V_{Center} = center of map in the vertical coordinate.

W = line width in km s^{-1}.

B.   From Sensitivity to Total Time

Observers will be specifying their sensitivities in either units of flux density (S in Jy = 10^{-26} Watts m^{-2} s^{-1}), temperature as defined by the $T_R{}^*$ temperature scale (i.e., as if the observations were made above the Earth's atmosphere), or temperature as defined by the T_A temperature scale (i.e., as observed from the surface of the Earth). If the user has specified they want to use the flux density or $T_R{}^*$ scales, then the calculator should first convert the user-given sensitivity to its equivalent in the T_A temperature scale. Thus, the calculator will perform either of the following two calculations, depending upon which units the user decides to start from:

$$\sigma_{T_A} = \frac{\eta \cdot \pi \cdot DishRadius^2}{2k \cdot e^{\tau \cdot AirMass}} \cdot \sigma_S \qquad \text{3-1}$$

$$\sigma_{T_A} = \frac{\eta}{e^{\tau \cdot AirMass}} \cdot \sigma_{T_R^*} \qquad \text{3-2}$$

The dish radius is dependent upon the receiver's feed illumination, which in the case of multipixel systems (e.g. MUSTANG) can differ substantially from the GBT's nominal 50-m radius.

Once σ_{T_A} is known, inverting the radiometer equation allows us to derive the effective integration time via:

$$t_{\text{eff}} = \left(\frac{K_1 \cdot T_{sys}}{\sigma_{T_A}}\right)^2 \left(\frac{1}{K_2 \cdot 10^6 \cdot BW \cdot N_{Samp}^{Uncorr}}\right) \qquad \text{3-3}$$

3.B.1   Total Time from Effective Integration Time When Differencing Signal and Reference Observations

Most observing modes require differencing observations of the source (on or signal) position (or frequency) and a reference (or off) position (or frequency) where one may spend different amount of time on each. Since both the signal and reference observations have noise, the resulting difference will

be nosier than the signal observation. To combat this extra noise, it's a common practice to smooth the reference observation or to average multiple reference observations. But, even with reference smoothing/averaging, the effective integration time is always less than the time spent on signal or reference and is even less than the time spent on both signal and reference combined.

From the theory of the propagation of errors:

$$t_{\text{eff}} = \frac{t_{\text{Sig}} \cdot (N_{\text{RefSmthAvrg}} \cdot t_{\text{Ref}})}{t_{\text{Sig}} + (N_{\text{RefSmthAvrg}} \cdot t_{\text{Ref}})}$$

3-4

If there is no overhead involved in the observing, then the total time needed for an observation is $t_{\text{Sig}} + t_{\text{Ref}}$. But, still there is insufficient information to derive a total time from t_{eff}. Observers who will be using the calculator to convert sensitivity into a time won't know either t_{Sig} or t_{Ref} but they will know, or their observing mode will dictate, a value for:

$$R_{\text{SigRef}} = t_{\text{Sig}}/t_{\text{Ref}}$$

3-5

And now we have enough information to derive a total time (ignoring overhead). A bit of algebra in combining equations 3-4 and 3-5 yields:

$$t_{\text{Total}} = t_{\text{Sig}} + t_{\text{Ref}} = t_{\text{eff}} \cdot \frac{(R_{\text{SigRef}} + N_{\text{RefSmthAvrg}})(R_{\text{SigRef}} + 1)}{R_{\text{SigRef}} \cdot N_{\text{RefSmthAvrg}}}$$

3-6

At this point, it will be useful to introduce the quantity that various memos have been calling the Effective Integration Time (EST) = $T_{sys} \cdot e^{\tau \cdot AirMass}$. In order to correct our observing times for the relative loss of efficiencies due to tracking or surface errors (concepts I will introduce in §3F), I will define:

$$EST_{TS} = \frac{EST}{\sqrt{\eta_{Track}\eta_{Surf}}} = \frac{T_{sys} \cdot e^{\tau \cdot AirMass}.}{\sqrt{\eta_{Track}\eta_{Surf}}}$$

3-7

Then, after combining equations 3-1, 3-2, 3-3, and 3-6, one gets our final equations for converting between a user-specified σ_S, $\sigma_{T_R^*}$, or σ_{T_A} and the total time needed for an observation.

$$t_{\text{Total}} = \left(\frac{2k \cdot K_1 \cdot EST_{TS}}{\eta \cdot \pi \cdot DishRadius^2 \cdot \sigma_S}\right)^2 \left(\frac{(R_{\text{SigRef}} + N_{\text{RefSmthAvrg}})(R_{\text{SigRef}} + 1)}{K_2 \cdot 10^6 \cdot BW \cdot N_{Samp}^{\text{Uncorr}} \cdot R_{\text{SigRef}} \cdot N_{\text{RefSmthAvrg}}}\right)$$

3-8

$$t_{\text{Total}} = \left(\frac{K_1 \cdot EST_{TS}}{\eta \cdot \sigma_{T_R^*}}\right)^2 \left(\frac{(R_{\text{SigRef}} + N_{\text{RefSmthAvrg}})(R_{\text{SigRef}} + 1)}{K_2 \cdot 10^6 \cdot BW \cdot N_{Samp}^{\text{Uncorr}} \cdot R_{\text{SigRef}} \cdot N_{\text{RefSmthAvrg}}}\right)$$

3-9

$$t_{\text{Total}} = \left(\frac{K_1 \cdot EST_{TS}}{\sigma_{T_A} \cdot e^{\tau \cdot AirMass}}\right)^2 \left(\frac{(R_{\text{SigRef}} + N_{\text{RefSmthAvrg}})(R_{\text{SigRef}} + 1)}{K_2 \cdot 10^6 \cdot BW \cdot N_{Samp}^{\text{Uncorr}} \cdot R_{\text{SigRef}} \cdot N_{\text{RefSmthAvrg}}}\right)$$

3-10

Once t_{Total} is known, the calculator should also display values for $t_{Sig} = t_{Total} \cdot R_{SigRef}/(R_{SigRef} + 1)$ and $t_{Ref} = t_{Total}/(R_{SigRef} + 1)$.

3.B.2   Total Time When Not Differencing Signal And Reference Observations

Some observing modes do not require taking a reference observation, which implies that $t_{Total}=t_{eff}$.   In this case, the equivalent of equations 3-8, 3-9, and 3-10 are:

$$t_{Total} = \left(\frac{2k \cdot K_1 \cdot EST_{TS}}{\eta \cdot \pi \cdot DishRadius^2 \cdot \sigma_S}\right)^2 \left(\frac{1}{K_2 \cdot 10^6 \cdot BW \cdot N_{Samp}^{Uncorr}}\right) \qquad \text{3-11}$$

$$t_{Total} = \left(\frac{K_1 \cdot EST_{TS}}{\eta \cdot \sigma_{T_R^*}}\right)^2 \left(\frac{1}{K_2 \cdot 10^6 \cdot BW \cdot N_{Samp}^{Uncorr}}\right) \qquad \text{3-12}$$

$$t_{Total} = \left(\frac{K_1 \cdot EST_{TS}}{\sigma_{T_A} \cdot e^{\tau \cdot AirMass}}\right)^2 \left(\frac{1}{K_2 \cdot 10^6 \cdot BW \cdot N_{Samp}^{Uncorr}}\right) \qquad \text{3-13}$$

C.   From Total Time to Sensitivity

Equations 3-8 through 3-13 are the overall equations to use when converting from the user's desired sensitivity to a total observing time. Simple inversions of these equations allow one to go from a user-supplied total time to the sensitivity that time will achieve. The inversions of the four equations are, respectively:

With reference observations:

$$\sigma_S = \left(\frac{2k \cdot K_1 \cdot EST_{TS}}{\eta \cdot \pi \cdot DishRadius^2}\right)\sqrt{\frac{(R_{SigRef} + N_{RefSmthAvrg})(R_{SigRef} + 1)}{K_2 \cdot 10^6 \cdot BW \cdot N_{Samp}^{Uncorr} \cdot R_{SigRef} \cdot N_{RefSmthAvrg} \cdot t_{Total}}} \qquad \text{3-14}$$

$$\sigma_{T_R^*} = \left(\frac{K_1 \cdot EST_{TS}}{\eta}\right)\sqrt{\frac{(R_{SigRef} + N_{RefSmthAvrg})(R_{SigRef} + 1)}{K_2 \cdot 10^6 \cdot BW \cdot N_{Samp}^{Uncorr} \cdot R_{SigRef} \cdot N_{RefSmthAvrg} \cdot t_{Total}}} \qquad \text{3-15}$$

$$\sigma_{T_A} = \left(\frac{K_1 \cdot EST_{TS}}{e^{\tau \cdot AirMass}}\right)\sqrt{\frac{(R_{SigRef} + N_{RefSmth})(R_{SigRef} + 1)}{K_2 \cdot 10^6 \cdot BW \cdot N_{Samp}^{Uncorr} \cdot R_{SigRef} \cdot N_{RefSmthAvrg} \cdot t_{Total}}} \qquad \text{3-16}$$

Without reference observations:

$$\sigma_S = \left(\frac{2k \cdot K_1 \cdot EST_{TS}}{\eta \cdot \pi \cdot DishRadius^2}\right)\sqrt{\frac{1}{K_2 \cdot 10^6 \cdot BW \cdot N_{Samp}^{Uncorr} \cdot t_{Total}}} \qquad \text{3-17}$$

$$\sigma_{T_R^*} = \left(\frac{K_1 \cdot EST_{TS}}{\eta}\right)\sqrt{\frac{1}{K_2 \cdot 10^6 \cdot BW \cdot N_{Samp}^{Uncorr} \cdot t_{Total}}} \qquad \text{3-18}$$

$$\sigma_{T_A} = \left(\frac{K_1 \cdot EST_{TS}}{e^{\tau \cdot AirMass}}\right)\sqrt{\frac{1}{K_2 \cdot 10^6 \cdot BW \cdot N_{Samp}^{Uncorr} \cdot t_{Total}}} \qquad \text{3-19}$$

The calculator should also display values for $t_{Sig} = t_{Total} \cdot R_{SigRef}/(R_{SigRef} + 1)$ and $t_{Ref} = t_{Total}/(R_{SigRef} + 1)$.

D. Continuum Caveats

All receivers have a sensitivity limit from 1/F gain instabilities but a few systems that were explicitly designed for continuum observations (e.g., Mustang and the Ka-Band receiver but only when used with the CCB backend) have much less of an issue with 1/F instabilities. These gain instabilities essentially place an upper limit on $t_{Total} \cdot BW$ – beyond a certain point, increasing the bandwidth or the amount of observing time does not improve one's sensitivity.

Since we have yet to characterize the 1/F characteristics of most of our receivers, the sensitivity calculator can only provide rough guidelines. The calculator should warn a user that they have probably exceeded the 1/F limitations of the receiver whenever $t_{Total} \cdot BW$ exceeds certain values. Until the support staff has a chance to comment, preliminary guesses are:

System	$t_{Total} \cdot BW$ Limit
Mustang	10^{11}
Ka-Band with CCB	10^{11}
All Other Systems	10^{9}

There are some techniques for overcoming the 1/F limit, such as making multiple maps with fast slewing or switching. If the user's planned observation exceeds the 1/F limit, the calculator may suggest that the user probably should consider justifying in their proposal how they expect to overcome the 1/F limit.

E. Confusion Limit

Sensitivities are also limited by the confusion limit from multiple background sources. The confusion limit for the calculator depends upon the topocentric observing frequency (in MHz), the FWHM beam width of the telescope (in arc minutes) at that frequency, and the user's chosen units for sensitivity.   It is recommended that one stay under five times the confusion limit for a reliable detection.

Units	5x Confusion Limit	
S	$0.13 \cdot \dfrac{FWHM^2}{Frequency^{0.7}}$	3-20
T_R^*	$0.41 \cdot \dfrac{(DishRadius \cdot FWHM)^2}{2k \cdot Frequency^{0.7}}$	3-21

T_A	$0.41 \cdot \dfrac{\eta \cdot (DishRadius \cdot FWHM)^2}{2k \cdot Frequency^{0.7} \cdot e^{\tau \cdot AirMass}}$	

(Note that the above equations will work for receivers like Mustang which have a flat feed pattern that illuminates less than the 50-m radius of the GBT.)

If the user is entering a sensitivity to derive a t_{Total}, then the calculator should warn the user whenever the user enters a sensitivity that is smaller than the corresponding value from the above table. If the user is entering a time in order to derive sensitivity, then the calculator should warn the user whenever the calculated sensitivity is smaller than the corresponding value from the above table. In both cases, the warning should present the value of the confusion limit and state the user is trying to observe to a sensitivity that is less than the recommendation of five times the confusion limits. It may also offer the suggestion that the user may want to justify how they will try to circumvent that limit. In any case, the calculator needs to display in its output window the confusion limit in the units the user has selected for his or her sensitivity.

F. Determining Values for EST_{TS}, EST_0, Attenuation, η, Air Mass, and T_{sys}

Equations 3-8 through 3-19 depend upon values for EST_{TS} which in turn depends upon τ, air mass (i.e., elevation), receiver temperature, T_{Atm}, background source temperature, spillover and the cosmic microwave background as well as the yet-to-be defined quantities η_{Track} and η_{Surf}. The calculator, of course, won't know the details of the weather conditions or elevation ranges over which the observations will happen. Instead, it will make the assumption that the observations will happen under typical opacity and wind conditions, as determined by DSS simulations, for the chosen trimester, topocentric frequency, and receiver. It also will assume observations will be taken symmetrically around the meridian to the Hour Angle or elevation limits that the DSS simulations have determined are reasonable for the user's frequency and receiver.

3.F.1 EST_{TS}

The DSS simulators can in principle provide the calculator with enough information that one can directly estimate a typical value for EST_{TS} for most observing setups. The DSS quantity η_{DSS} is an observing efficiency with respect to time that is normalized to the best conditions that are possible for the observing frequency, receiver, and source elevation. That is, a value of $\eta_{DSS} = 0.5$ suggests one will need twice as much observing time to achieve the same sensitivity as one would under the best opacity, wind, surface, … conditions. η_{DSS} is the product of the observing efficiency for atmospheric conditions (η_{Atm}), tracking errors due to the telescope's pointing accuracy under various wind conditions (η_{Track}) and surface errors (η_{Surf}). $\eta_{Atm} = (EST_0/EST)^2$ where EST_0 is the effective system temperature for the best possible conditions.

We will want to use η_{DSS} to derive the EST_{TS} in order to correct the observing time for loss of efficiency due not just to opacity but also for winds and the surface. Since:

$$\eta_{DSS} = \eta_{Track}\eta_{Surf}\left(\frac{EST_0}{EST}\right)^2 = \left(\frac{EST_0}{EST_{TC}}\right)^2 \qquad \text{3-23}$$

one would like to substitute $EST_{TS} = EST_0/\sqrt{\eta_{DSS}}$ into equations 3-8 through 3-19. But that would be wrong. η_{DSS} does not take into consideration the affects of any strong background source and, thereby, is too pessimistic. For example, observing the moon (T_{BG}=300 K) with our 22 GHz receiver under typical weather conditions (τ=0.06, air mass=2) with no winds should have an EST_{TS}~360 K, yet inverting equation 3-23 gives either EST_{TS}~60 K or ~815 K, depending upon assumptions made in how to include background sources. Under most conditions it is possible to correct to our desired accuracy the definitions of η_{DSS} and EST_{TS} to properly compensate for a background source. Instead of just inverting equation 3-23 , one uses:

$$EST_{TS} = \frac{T_{BG} + T_{BG}^{Gal}}{\sqrt{\eta_{Track}\eta_{Surf}}} + \frac{EST_0}{\sqrt{\eta_{DSS}}} \qquad \text{3-24}$$

Thus, the DSS simulators need to supply values for η_{DSS} and the product $\eta_{Track}\,\eta_{Surf}$, all of which can be assumed to be frequency and receiver dependent.

3.F.2 EST_0

EST_0 is obtained from:

$$EST_0 = \left(T_{Rcvr} + T_{Spill} + T_{Atm}\right)\cdot e^{\tau_0} - (T_{Atm} - T_{CMB}) \qquad \text{3-25}$$

where τ_0 is the best possible opacity at the observing frequency.   We can assume T_{Spill} (= 3 K) and T_{CMB} (=2.7 K) are receiver and frequency independent. T_{Rcvr} is receiver and frequency dependent and T_{Atm} is frequency and weather dependent. For the purposes of the calculator, it should be sufficient to use average values of T_{Atm} for the user's choice of trimester. Values for τ_0, T_{Rcvr} , and T_{Atm} should be stored in the internal database for the various trimesters with a frequency resolution no worse than 1000 MHz.

3.F.3   Attenuation ($e^{\tau\,AirMass}$)

Note that equations 3-10, 3-13, 3-16, 3-19, and 3-24 also require knowing $e^{\tau\,AirMass}$, that is the expected, typical (not best) atmospheric attenuation.   With a bit of algebra we can provide a value for $e^{\tau\,AirMass}$ from values already available to the calculator:

$$e^{\tau\cdot Airmass} = \frac{EST_0\sqrt{\dfrac{\eta_{Track}\eta_{Surf}}{\eta_{DSS}}} + (T_{Atm} - T_{CMB})}{T_{Rcvr} + T_{Spill} + T_{Atm}} \qquad \text{3-26}$$

3.F.4 η

If the user has specified they will be observing a point source, the value to use for η in the above equations is the telescope's nominal night-time aperture efficiency (η_A):

$$\eta = \eta_A = \eta_0 \cdot e^{-\left(1.45\times10^{-5}\cdot Frequency\right)^2}$$

<div align="right">3-27</div>

where η_0 depends upon the feed illumination and illumination pattern, is receiver dependent, and stored in the internal database.

For non-point-like sources, one augments the value for η_A using:

$$\eta = \eta_A \cdot f(\theta_{Source})$$

<div align="right">3-28</div>

Where $f(\theta_{Source})$ is a function of source size and is similar in shape to Figure 8 of Baars (IEEE Trans Antenna Propagat., vol AP-21, no 4., pp 461-474, 1973). To the 10% accuracy of the calculator, the same function can be used for all receivers.

3.F.5 Air Mass

The calculator doesn't need values for air mass. Yet, it might be useful to observers if we were to display an representative value for air mass.   It is sufficiently accurate for the sensitivity calculator to use csc(El) as an approximation for air mass. From the source declination, one can estimate the elevation at transit (El_{Max}= Declination + 51.57°). From the DSS simulations, the calculator will have the suggested minimum elevation.   Once the minimum and maximum elevations are known, a value for the typical air mass can be roughly given by:

$$\langle AirMass \rangle = \frac{57.29 \cdot ln\left(\frac{\tan(El_{Max}/2)}{\tan(El_{Min}/2)}\right)}{El_{Max} - El_{Min}}$$

<div align="right">3-29</div>

Or more accurately using a function I can supply.

3.F.6 Opacity (τ)

I don't recommend the calculator display a value for τ but instead display the attenuation ($e^{\tau\,AirMass}$) as calculated in §3.F.3.   If at some point it is deemed that we need to display a typical τ, there's no absolutely accurate way to do so without seriously augmenting the information the calculator will need. Instead, I suggest we use the rather rough approximation of combining the EST_{TS} of §3.F.3 with the air mass of §3.F.5:

$$\tau = \frac{ln\left(\frac{EST_0\sqrt{\frac{\eta_{Track}\eta_{Surf}}{\eta_{DSS}}} + (T_{Atm} - T_{CMB})}{T_{Rcvr} + T_{Spill} + T_{Atm}}\right)}{\langle AirMass \rangle}$$

<div align="right">3-30</div>

3.F.7 Tsys

The calculator will have enough information to display a typical T_{Sys} for the planned observations by combining the results of equations 3-24 and 3-26:

$$T_{Sys} = \frac{EST_{TS} \cdot \eta_{Track}\eta_{Surf}}{e^{\tau \cdot AirMass}} \qquad \textbf{3-31}$$

G. Determining Values for K_1, K_2, $N_{RefSmthAvrg}$, and N_{Samp}^{Uncorr}

3.G.1 K_1 and K_2

Values for K_1 and K_2 are backend and backend mode dependent. Values will be retrieved from the calculator's internal information according to the answers users have supplied to their hardware questions. For all backends except for the GBT Spectrometer (ACS):

Backend	K_1	K_2
Mustang, Radar, CCB, Mark V, GUPPI, DCR	1	1
Spectral Processor	1.30	1.21

The value of K_1 for the GBT Spectrometer depends upon whether the observations are made in 3- or 9-levels modes. For the 200 and 800 MHz bandwidth modes of the correlator, only the 3-level mode is possible. But, for the 12.5 and 50 MHz bandwidth modes, the backend allows one to pick either 3 or 9 level sampling. Only those observations that need the highest frequency or velocity resolutions should use 3-level sampling since it is far less efficient than 9-level sampling. The breaking point as to whether to use 3- or 9-level depends upon the user's expected bandwidth after smoothing (BW) and the specified number of spectral windows ($N_{Windows}$) in the following way:.

GBT Spectrometer Mode	BW/$N_{Windows}$	Sampling	K_1	K_2
200 or 800 MHz	**Any**	**3-level**	1.235	1.21
50 MHz	**< 0.38 MHz**	**3-level**	1.235	1.21
	>= 0.38 MHz	**9-level**	1.032	1.21
12.5 MHz	**< 1.52 MHz**	**3-level**	1.235	1.21
	>= 1.52 MHz	**9-level**	1.032	1.21

3.G.2 N$_{\text{RefSmthAvrg}}$

The value for N$_{\text{RefSmthAvrg}}$ is obtained from:

$$N_{\text{RefSmthAvrg}} = N_{RefAvrg} \cdot BW_{Ref}/BW \qquad \text{3-32}$$

where N$_{\text{RefAvrg}}$, BW, and BW$_{\text{Ref}}$ come from the answers in §2.E.1.

3.G.3 N$_{\text{Samp}}^{\text{Uncorr}}$

N$_{\text{Samp}}^{\text{Uncorr}}$ represents how the sensitivity improves by observing with multiple samplers, whether these are samplers that observe orthogonal polarizations or samplers of the same polarization that observe the same range in frequency. For example, from sampling theory, a 3-level autocorrelation backend has about 80% the sensitivity of a 9-level backend. That difference in sensitivity, about a factor of 40% in time, can be recovered if one were to observe the same frequency range with 4 samplers. Thus, N$_{\text{Samp}}^{\text{Uncorr}}$ represents the degree to which the data streams from samplers are uncorrelated and is a product of terms that can be represented by:

$$N_{\text{Samp}}^{\text{Uncorr}} = \text{DualPol} \cdot \text{ObervingMethod} \cdot \text{Sensitivity}(N_{\text{Overlap}}) \qquad \text{3-33}$$

N$_{\text{Overlap}}$ is the number of samplers that are observing with the same beam and polarization, as determined from the questions of §2.E.1.

- DualPol = 2 if the user has specified in §2.E.1 they will be averaging polarizations, otherwise = 1.
- ObservingMethod = 2 if the user has specified in-band frequency switching and any of the 'nodding' observation types. Otherwise = 1.
- I will define Sensitivity(i) such that Sensitivity(1) = 1, Sensitivity(2)= the improvement in sensitivity by having 2 overlapping samplers, …, Sensitivity(n)= the improvement in sensitivity by having n overlapping samplers. Since the improvement in sensitivity depends upon the backend and backend mode, the Sensitivity table needs to be stored internally to the calculator (see §5).

H. Other Calculations

3.H.1 Calculating FWHM beam size

The FWHM beam width of the GBT depends upon the feed illumination pattern and observing frequency. With the introduction of Mustang and the possibility of beam forming arrays, we now have receivers whose illumination is not Gaussian and may not cover the full aperture of the GBT. Thus, equation 1 of the GBT Proposer's Guide (Minter, http://www.gb.nrao.edu/gbtprops/man/GBTpg.pdf) needs to be generalized. To prepare for that generalization, I expect the internal database will need to hold some description of each receiver's illumination. Until then, the prototype calculator can use the equations in Toney's guide.

3.H.2 Calculating topocentric frequency, topocentric frequency resolution, velocity resolution, and velocity coverage.

The calculator in a number of places convert a rest frequency to a topocentric frequency using a supplied definition of the Doppler correction and either a velocity or redshift (z). Column 3 of Table 3 of http://www.gb.nrao.edu/~fghigo/gbtdoc/doppler.html (Ghigo) describes how this should be done. In that memo, f0 = rest frequency, V = source velocity, and c = speed of light (3.00×10^5 km s^{-1}).

The calculator is asked to calculate a topocentric frequency spacing and resolution from the receiver's bandwidth. For the purposes of the calculator, the spacing will be the bandpass selected by the user in Questions2.B.1 divided by the maximum number of channels that the user's configuration will allow. The resolution is the spacing multiplied by the resolution factor for the chosen backend mode, also stored internally.

The calculator is asked to calculate a topocentric frequency resolution from a supplied definition of the Doppler correction and either a velocity resolution or frequency resolution in the source's rest frame.

- To convert from a rest frame frequency resolution to a topocentric frequency resolution:
    - Evaluate Column 3 of Table 3 using f0'=f0 + Δf/2
    - Then repeat for f0'=f0 - Δf/2
    - Use the absolute value of the difference of the above two results.
- To convert a velocity resolution in the rest frame to a topocentric frequency resolution:
    - Evaluate Column 3 of Table 3 using V'=V + Δv/2
    - Then repeat for V'=V - Δv/2
    - Use the absolute value of the difference of the above two results.

4 Sub-Calculators and Other Tools

Releasing by fall a feature-rich sensitivity calculator should be a high priority. But, there are a number of sub-calculators and helpful tools that should be available from the calculator. Let's not again repeat our mistakes and release a product that is only 80% done. The priorities of delivering these extra tools should be such that they are built into the development schedule for the tool. We should postpone the delivery of these sub-tools only if that work would jeopardize the development of the main calculator.

Each tool uses some of the values from the main calculator. Most tools will produce results that modify values in the main calculator. All provide some information that should be included in the main calculator's overall results window.

A. Extragalactic HI Sub-Calculator

One of the bread-and-butter projects for the GBT is extragalactic HI observations. A useful sub-calculator we should supply encapsulates the calculations found in the appendix of the GBT "Proposal Guide" (http://www.gb.nrao.edu/gbtprops/man/GBTpg.pdf). The appendix shows how one can estimate the sensitivity of an extragalactic HI observation in units of solar masses. The equations in the appendix assume an explicit observing mode and backend, a specific efficiency and a high observing

elevation. Thus, the equations need to be coaxed into a more general representation that will cover the other observing modes and hardware that have been used with this science. The appendix also does not produce exactly the correct results since it ignores the difference between T_A and $T_R{}^*$.

As with the main calculator, some users will want to estimate sensitivity from time but others will want to estimate the amount of time needed to achieve a given sensitivity.   If the user specifies in the main calculator that they are estimating sensitivity from a user-specified observing time, and they then bring up the extragalactic HI sub-calculator, the main calculator needs to automatically switch to an intensity scale of Jy, regardless of the units specified by the user. The sub-calculator takes the sensitivity derived by the main calculator *in units of S*, asks the user for values for the distance to the galaxy in Mpc (D_{Mpc}) and the expected width of the spectral line of interest in km s^{-1} (W), and then displays the resulting HI sensitivity in units of solar masses:

$$\sigma_{M_{HI}} = 2.4 \times 10^5 \cdot D_{MPC}{}^2 \cdot \sigma_S \cdot \sqrt{W/\Delta v} \text{ (units of } M_\odot\text{).}$$
<div align="right">4-1</div>

Note that the calculator needs to pick up from the main calculator the value of Δv, the velocity resolution in units of km s^{-1}. As the user changes values in the main calculator that alter the value of σ_S, the sub-calculator should automatically use the new σ_S, to update $\sigma_{M_{HI}}$.

If the user specifies in the main calculator that they are estimating time from a user-specified sensitivity, and they then bring up the extragalactic HI sub-calculator, the main calculator needs to convert to the intensity scale of Jy and then disables the user's ability to enter a sensitivity since the sensitivity will now be generated by the sub-calculator. The sub-calculator asks the user for their sensitivity in units of solar masses, D_{Mpc} and W and then displays:

$$\sigma_S = \sigma_{M_{HI}}/\left(2.4 \times 10^5 \cdot D_{MPC}{}^2 \cdot \sqrt{W/\Delta v}\right).$$
<div align="right">4-2</div>

The main calculator uses automatically the sub-calculator's value for σ_S to derive the observing time. As the user adjusts values in the sub-calculator, the main calculator should automatically pick up and use the altered sub-calculator's value for σ_S to derive updated observing time estimates.

Note that the channel width should not be wider than the galaxy's velocity width because the observations will suffer from lost sensitivity due to channel dilution. Whenever W is smaller than Δv, the calculator should display a warning message stating that the calculations will be inaccurate due to channel dilution and suggest that they should make Δv narrower by making BW narrower.

B.   *Mapping Sub-Calculator*

One area that observers constantly estimate badly is the time needed to complete a map. The current mapping calculator, who's intended user is a skilled GBT observer, has led many a staff member or observer to the wrong conclusions. The current mapping calculator does not integrate with the sensitivity calculator, which further confuses users since often the concept of on- and off-source times mean different things to the two calculators. Integrating a redesigned mapping calculator into the

sensitivity calculator should reduce the number of instances when a user has misunderstood how to properly map with the GBT or specified their mapping time incorrectly.

If the user has specified in the main calculator that they will be performing a mapping experiment, the mapping sub-calculator should be made available.   The main calculator will supply the sub-calculator with the values for the topocentric observing frequency, the effective diameter of the telescope's dish (which is receiver dependent, e.g., with Mustang), observing mode, t_{Sig}, t_{Ref}, and t_{Total}. As the user changes the values of these in the main calculator, the sub-calculator should see and use the changed values. Only rectangular maps will be covered by the proposed calculator.

The mapping calculator needs to know the amount of time spent per position in the map. But, is that time per beam, per Nyquist cell, or per sample? It would be too complicated or confusing to give users a choice, and no one unit seems to be the best, so I will just pick time per sample since it is to me the system that is the least effort to program.

The user will select their mapping type from one of the following: *On-The-Fly, On-The-Fly with Reference, Pointed,* and *Pointed with Reference*.   The user will be asked for the vertical extent of the map (v) and a rough value of V_{Center}, the center of the map in the vertical coordinate system, both in fractional degrees. *The sub-calculator will not need to know whether that coordinate system is Az/El, Ra/Dec, Galactic, etc*. The user will also be asked whether or not they have corrected for CosV, the horizontal compression of a region due to observing a rectangular region on the spherical sky. The default values will be CosV is on, v=1, and V=0.   The calculator will then ask for either the CosV corrected horizontal extent of the map (h) or the non-corrected horizontal extent (H), depending upon whether the user has stipulated that the CosV was or was not performed. If h is given (i.e., CosV was used), the sub-calculator should show and store a value for H = h/cos(V_{Center}). If H is given (CosV was not used), the sub-calculator should show and store a value for h = H·cos(V_{Center}).

If either of the *'with Reference'* map types is selected, the user will be asked to insert a rough estimate in degrees of the distance between the map center and reference position. The calculator will at first display a default of $Distance_{Ref} = 2 \cdot \sqrt{h^2 + v^2}$ in fractional degrees. To provide a good estimate of the mapping time, the sub-calculator will need to estimate and display the move time between the center of the map and the reference position ($t_{RefMove}$). Since the sub-calculator cannot know the details of the actual moves the telescope will perform, I suggest we use an average of the move times for each axis. During commissioning, we found that move times in seconds can be roughly estimated by:

$$t_{Move} = Maximum\ (15s, 12s + 3 * Distance)$$ **4-3**

The sub-calculator should perform some integrity checks between the mapping mode and the switching mode selected in the main calculator. The sub-calculator should warn users if they have selected a *'with Reference'* map but have not requested a switching mode of 'Total Power, Position Switching'. If they have selected a non-Reference map but have specified in the main calculator a switching mode of 'Total Power, Position Switching', the calculator should inform (not warn) the user that their reference

observations will need to be taken from within the map data itself. The user should be warned that a map using the NOD switching sub-type is not supported.

If the user in the main calculator has specified that they will be using more than one beam of a multi-beam receiver, then the exact mapping time will not be covered by this calculator. Except for Mustang observations, the details of mapping patterns, overlaying beam tracks, etc. is not yet established for us to program a suitable mapping calculator. Instead, the sub-calculator should inform the user that the calculated time and sensitivity estimates will not reflect the use of more than one beam. The calculator should warn the user if the beam separation of the chosen receiver is more than either 2h or 2v since such small maps will not be able to take good advantage of multiple beams.

4.B.1   Pointed Maps

A *Pointed Map* moves the telescope to the first position in the map grid, observes for a set time, then moves and settles on the next position in the grid, and so on. It is not important to the calculator whether '*Pointed* 'maps proceed row by row, column by column, top to bottom, etc but, to keep this discussion simple, the wording I will use will be as if the map is executed from top to bottom.   The pattern of moving from column to column in a row repeats until a row is completed. Then subsequent rows are observed until the map is completed.

A *Pointed Map with Reference* is identical except after every n_{Off} observations the map will be interrupted, the telescope moves to a nearby position to make a reference observation, and then picks up the map where it left off. The sub-calculator will at first display a default $n_{Off} = 1$ that the user can then modify.

For proper Nyquist sampling of an area, the calculator will use 1.1 as a default value for the amount by which the rows and columns of the map will be oversampled (f_h$_{OverSample}$ and f_v$_{OverSample}$). Then, it will use from the main calculator the topocentric frequency (in MHz) and the effective radius of the telescope (in meters) to provide defaults for the angular change in positions from column to column and from row to row (in arc minutes):

$$\Delta v_{Default} = \frac{257830/f\_v_{OverSample}}{DishRadius \cdot Frequency} \qquad \text{4-4}$$

$$\Delta h_{Default} = \frac{257830/f\_h_{OverSample}}{DishRadius \cdot Frequency} \qquad \text{4-5}$$

After displaying the default values, the user can alter the values of Δh and Δv and the software will display updated values of f_h$_{OverSample}$ and f_v$_{OverSample}$ that would produce the user's Δh and Δv. It will also report ΔH = Δh/cos(V), also in arc minutes. If either of the fractional oversampling values are greater than one, a warning should appear (though not in too a distracting way) that the user has specified a map that will undersample the object. The calculator will next display the number of rows and columns in the map, $N_v = 60 \cdot v/\Delta v$ and $N_h = 60 \cdot h/\Delta h$, and the total number of observed positions $N_v \cdot N_H$. The software should round up when calculating N_V and N_H. The calculator can then use the maximum of Δh and Δv and equation 4-3 to roughly estimate the time to move

between pixels in the map ($t_{MapMove}$). Since most maps will have Δh and $\Delta v < 1°$, the calculator may use $t_{MapMove} =15s$.

We now need t_{Pixel}, the amount of time the telescope will observe each pixel in the map, whose default value should be the same as t_{Sig} from the main calculator. The user should be able to modify t_{Pixel} but, if they do so, the calculator should warn that this is non-standard and it will not be able to properly use the results of the mapping calculator. Finally, we can estimate the time it will take to make a map:

Pointed Map   **4-6**
$$t_{Map} = N_v \cdot N_H \cdot (t_{Pixel} + t_{MapMove})$$
Pointed Map With Reference   **4-7**
$$t_{Map} = N_v \cdot N_H \cdot [t_{Pixel} + t_{MapMove} + (t_{Ref} + t_{RefMove})/n_{Off}]$$

4.B.2   On-The-Fly Maps

On-The-Fly maps slew the telescope as data are being taken. Unlike *Pointed Maps*, the direction of the slew is important for the sensitivity calculator. A map which slews parallel to the horizontal axes of the observer's coordinate system (i.e., slews along a row) is known as a RaLong map. A map that slews parallel to the vertical axes (i.e., slews along a column) is known as a DecLat map. Thus, the user should select whether the direction of the slew will be in the horizontal or vertical direction. The user should also select whether or not each row in the map will be attacked from the same direction, which is an important consideration for large, low-frequency maps. The defaults are for horizontal slews and attacking always from the same direction.

An *On-The-Fly Map with Reference* is identical except after every n_{Off} strips the map will be interrupted, the telescope moves to a nearby position to make a reference observation, and then picks up the map where it left off. The sub-calculator will at first display a default $n_{Off} = 1$ that the user can then modify.

Because the telescope is slewing as it takes data, data are smeared along the direction of the slew. To reduce artifacts from the smearing, it is a recommended practice to oversample by at least a factor of three in the direction of the slew (Mangum, Emerson, Greisen, 2007, A&A, 474, 679). The sub-calculator will use equations 4-4 and 4-5 to derive Δh and Δv but will use 3.3 as the default for $f_{Oversample}$ for the slew axis and 1.1 for the stepping axis. Since novice observers may miss the reason for the different oversampling values, the calculator should inform the user that it is recommended to oversample by at least a factor of three in the direction of the slew.

Again, as the user changes the values for Δh and Δv, the sub-calculator should show the equivalent change in f_h$_{OverSample}$ and f_v$_{OverSample}$. As before, the sub-calculator will report $\Delta H = \Delta h/cos(V)$, also in arc minutes. If either of the fractional oversampling values are greater than one, a warning should appear (though not in too a distracting way) that the user has specified a map that will undersample the object. The calculator will next display the number of 'samples' in the map, $N_v = 60 \cdot v/\Delta v$

and $N_h = 60 \cdot h/\Delta h$, and the total number of observed 'samples' $N_v \cdot N_H$. The software should round up when calculating N_V and N_H.

We again need t_{Pixel}, which again usually equals t_{Sig}.   The calculator should display the amount of time it will take to slew through a row of a RaLong map ($t_{Row}=N_H \cdot t_{pixel}$) or a column in a DecLat map ($t_{Column}=N_V \cdot t_{pixe}$) as well as the slew rate (in °/min), either $\Delta h/ t_{Pixel}$ for RaLong or $\Delta v/ t_{Pixel}$ for DecLat. The sub-calculator should display an obvious error message if the slew rate exceeds the telescope's average maximum slew rate of 16°/min.

The time to move from pixel to pixel in the slew direction is already incorporated in t_{Row} or t_{Column} but we still need an estimate for $t_{MapMove}$, the overhead to move from row to row in a RALong map or column to column in a DecLat map. Estimates for $t_{MapMove}$ are derived from equation 4-3 but the distance to insert into the equation will depend upon the mapping direction and whether the map is uni- or bidirectional.

Map Type	Direction	Distance to Use in eq. 4-3
RaLong	Bi-directional	Δv
RaLong	Uni-directional	h
DecLat	Bi-directional	Δh
DecLat	Uni-directional	v

The total time to make the map is:

On-The-Fly, RALong Map:

$$t_{Map} = N_v \cdot (t_{Row} + t_{MapMove})$$

4-8

On-The-Fly, DecLat Map:

$$t_{Map} = N_h \cdot (t_{Column} + t_{MapMove})$$

4-9

On-The-Fly With Reference, RALong Map:

$$t_{Map} = N_v \cdot [t_{Row} + t_{MapMove} + (t_{Ref} + t_{RefMove})/n_{Off}]$$

4-10

On-The-Fly With Reference, DecLat Map:

$$t_{Map} = N_H \cdot [t_{Column} + t_{MapMove} + (t_{Ref} + t_{RefMove})/n_{Off}]$$

4-11

4.B.3   Final Results

Since maps are usually oversampled, and we've decided to use time per cell in the mapping calculator, the sensitivity of a Nyquist cell or beam in the final map is lower than that estimated by the main calculator.   To guide the user in to what to expect when making the final image, the sub-calculator should display the ratio of the sensitivity per Nyquist cell to the sensitivity per sample, $\sigma_{Nyquist}/\sigma_{Sample} = 1/\sqrt{\text{f\_h}_{OverSample} \cdot \text{f\_v}_{OverSample}}$ followed by the ratio of the sensitivity per beam to the sensitivity per sample $\sigma_{Beam}/\sigma_{Sample} = 0.6 \cdot \sigma_{Nyquist}/\sigma_{Sample}$

Once the user is finished with the mapping calculator, the main calculator should pick up and display in the overall results window the user chosen map type, values of v, h, H, V_{center}, Δh , Δv, f_h$_{OverSample}$, f_v$_{OverSample}$ N_V, N_H, t_{Pixel}, $t_{MapMove}$, and t_{map}. If 'On-The-Fly', it will display slew direction and slew rate and, depending upon the slew direction, either t_{Row} or t_{Column}. If a 'with Reference' map, the sub-calculator will display Distance$_{Ref}$, n_{Off} and $t_{RefMove}$.

Spectral-line Assistant

A common mistake users make in multi-spectral-line proposals pertains to the number of spectral windows that can be observed simultaneously. These mistakes often affect the amount of time needed for an experiment. Due to the subtleties of how receivers are connected to backends, even pro observers have been confused and requested more spectral windows than the hardware can accommodate. In these cases, the project needs twice the requested observing time to capture all lines. Or sometimes observers don't realize that a different hardware setup would require less time to accomplish the same science.
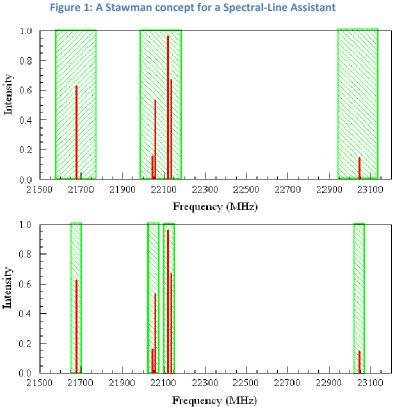
Various staff members have tried to create tools to help staff and observers make wise and physically possible hardware choices. For example, Paul Ruffle created an Excel spreadsheet to help staff determine the optimum setup. I suggest we encapsulate a slightly more sophisticated tool into the calculator for our users, especially neophytes to radio astronomy and the GBT.   We can retire the more rudimentary spectral-line advisors that Frank Ghigo and others are maintaining.

The spectral-line assistant will be an interactive, graphical display. The assistant needs certain information from the user that is gathered in two steps. It first asks the user for some preliminary information that is not available in the main calculator (though which could be imported from the PST in some future revision):

- The number of desired spectral lines (N_{lines}), which may not have an upper bound since a single spectral window can observe multiple lines simultaneously. Default = 1.
- A toggle that allows the user to choose between specifying line frequencies in their rest frame or topocentric frame. Default will be the same value as specified in the main calculator.
- If the user specified they will be entering frequencies in the line's rest frame, the user will be asked for the source's velocity (in km s^{-1}) and the desired definition of the Doppler shift (radio, optical, relativistic). Default values will be the same value as specified in the main calculator.

- The user will not be asked for the source velocity or Doppler definition if the user specified they will be entering frequencies in the topocentric frame.
- The user will then enter frequencies (in MHz) for their N_{lines}. Default will be whatever the main calculator is currently using.
- The user will be given the option of entering N_{lines} line strengths or line ratios (the assistant will treat either case the same). If no values are supplied, the assistant will assume values of one.

If the user has specified they are using the line's rest frame, the assistant will use the Doppler definition and source velocity to generate a table of N_{lines} rows with approximate topocentric frequencies (in MHz) and spectral resolutions (Δv_{MHz} in km s^{-1} MHz^{-1}) (see 3.H.2). Approximate topocentric frequencies should be more than sufficient. The assistant will know the observer's choice of receiver from the main calculator and should issue an obvious warning if any of the topocentric frequencies falls outside of the range covered by the receiver. The frequency limits are obtained from the internal information described in Toney's memo.

Figure 1: A Stawman concept for a Spectral-Line Assistant

The assistant now has either user-supplied or calculated topocentric frequencies, possibly intensities, and can generate a 'scatter' plot with drop lines with reasonable loose axes limits to make the plot look nice. Figure 1 is a hypothetical example with six user-specified lines, colored in red. From the internal information, and the user-specified backend and observing mode from the main calculator, the assistant will know the possible choices of backend bandwidths and the maximum number of possible

spectral windows. The logic of how to determine bandwidths and number of spectral windows is outlined in Toney's memo.

The assistant then asks its second set of questions. It presents to the user the list of possible bandwidths. After the user selects a bandwidth, it then allows the user to select the number of spectral windows ($N_{Windows}$), up to the maximum possible.   The assistant then draws $N_{Windows}$ boxes on the above-mentioned drop-line graph. The box widths correspond to the chosen bandwidth (see Figure 1 where the upper figure is an example where someone asked for two 200 MHz bandwidths and the lower is a request for four 50 MHz windows). The initial position of the boxes need not be centered on any of the spectral lines but can be anything that seems to look OK. The interface should display a table of the minimum, maximum, and center frequencies of each box, and the velocity coverage of each box (see §3.H.2).   Since the assistant also knows from Toney's memo the maximum possible number of channels each bandwidth can have, it may also be able to generate a columns in the table of the minimum possible velocity resolution per channel (see §3.H.2).

The user can then manipulate the x-axis position (i.e., the center frequencies) of the $N_{Windows}$ boxes, maybe by dragging boxes left and right with the mouse in the plot. The interface should update the table of values as the boxes are moved. In our example, the top panel shows a possible final setup where three 200 MHz bandwidths cover all the desired lines. The bottom example shows how four 50-MHz windows can cover the same lines.

Since the ratio of the frequency covered by a plot can be many times the bandwidth, we might need to have an x-axis zoom feature added to the plot. Whether such a feature is needed will depend upon the quality of the graph and, as such, may end up as a strong requirement.

Once users are satisfied they have the optimum configuration, the user can alter the main calculator's values for backend bandwidth and number of widows by hitting something like an "Apply" or "OK" in the interface. The user must also have the option of cancelling any application of the assistant's results to the main calculator.

The calculator should store various pieces of information from the assistant that is to be displayed in the calculator's overall output window. The information should document for posterity the user's intentions and facilitate the technical review performed by the staff.   This information should include at a minimum the user-supplied values for frequencies (if rest frequencies are specified, then also the user-specified Doppler definition, source velocity and the assistant's calculated topocentric frequencies; other wise just the user-supplied topocentric frequencies), and the center frequencies, bandwidth, velocity coverage, and spectral resolution of each window.

C.   RFI Assistant

Once the spectral-line assistant is available, a very useful feature for planning observing could be to overlay onto the spectral-line assistant's graph a plot of RFI as last measured by our monitoring station or by our GBT-produced RFI scans.   The latter data are easily available via simple HTTP calls as ASCII

text.   We've dreamed of such a user-friendly feature and now can tag this onto an infrastructure we're developing for other reasons.

The spectral-line assistant would require a user-selected toggle that would turn on and off the RFI overlay/assistant.   The topocentric frequency extent of the plot and user-specified receiver would suggest to the assistant the file that needs to be downloaded. Since the intensity scale of the RFI bears no relationship to the height of the lines drawn on the GUI, the GUI would rescale in the y-axis the overlaid RFI to fit the intensity scale of the GUI plot.   Since low-level RFI can be hidden in a full-scale plot, it's imperative that the GUI be able to rescale in the y-axis the overlaid RFI (in steps of 10^{-1}, 10^{-2}, 10^{-3} … 10^{-6}) but without rescaling the underlying mock spectral lines.

Since the RFI overlay is mostly for a user's immediate use, no results need be passed from the RFI assistant to the main calculator.   At most, maybe just a flag in the calculator's output window that states the user has examined the RFI plots.

5   Required Internal Information

In addition to the database information required to fulfill Toney's memo (see http://www.gb.nrao.edu/~tminter/PST/GBT-Resources-Table.pdf), there is a set of ancillary information the calculator needs for its own purposes. The descriptions above describe how this information will be used. Because this information is scattered throughout the memo, I thought it best to summarize these needs in a single location.

- Each receiver should have a description of its feed illumination pattern. In unusual cases, the illumination may be significantly frequency dependent that we will need a table of values for each receiver.
    - Gaussian or flat,
    - If flat, the radius to which it illuminates the dish (DishRadius)
    - If Gaussian, the feed taper to the 50-m radius of the GBT
- Each receiver should have values for η_0.
- Each receiver should have values for T_{Rcvr} that are to a frequency spacing of 1000 MHz or better.
- Each receiver should have a table giving its nominal frequency limits in MHz.
- A model of $f(\theta_{Source})$, the change in efficiency with source size.
- Each backend should have a table of K_1 and K_2 values and a way to derive these values from the hardware setup implied by Toney's memo and the answers to the user's hardware questions.
- Each backend needs a table of how noise improves by overlapping multiple samplers.
- A mathematical model of how aperture efficiency changes with topocentric frequency and observing elevation.   For now, we can assume the efficiency curve has no elevation dependency, only a frequency dependency.
- A model of the galactic background emission as a function of frequency and position.   I suggest we simply call existing software which will return the evaluation of the model for the user's position and frequency.

- From weather statistics, values for τ_0 (best opacity) and T_{Atm} as a function of frequency for each trimester and for the full year. Data should be spaced by 1000 MHz or better and probably to the same spacing as T_{Rcvr}.
- The DSS simulations needs to provide values for η_{DSS} and either the product $\eta_{Track}\eta_{Surf}$ or each term individually. Values should be for each trimester and should be spaced by 1000 MHz or better and probably to the same spacing as T_{Rcvr}.
- The DSS simulations need to provide stringency values so that the calculator can display the fraction of time or number of hours in a year or trimester that is suitable for the observer's choice of receiver and frequency. Values should be dependent upon frequency, receiver, and trimester and be spaced by 1000 MHz or better and probably to the same spacing as T_{Rcvr}.
- The DSS simulations need to provide minimum elevation limits as a function of Declination, receiver, frequency, and trimester.
- Models of the cumulative percentiles of how often winds are lower than a certain value. We will need models of wind statistics that cover the full year and statistics for each trimester.
- In order to provide estimates of the loss in efficiency or calibration accuracy due to winds, the DSS simulations need to provide either:
   - a table of the wind limits used in the simulations as a function of frequency and mathematical models of how a wind speed reduces the observing efficiency and increases the calibration uncertainty; or
   - a model or table relating the expected efficiency and increased calibration uncertainty as a function of frequency.

6 Appendices

A.   Overhead

Since overheads can account for 10 to 50% of the assigned telescope time, it becomes important to have observers submit proposals that use a project length that includes overhead in a reasonable way. Overhead is dependent upon observing modes and hardware as well as the calibration accuracy desired by the observers. The complexities of determining the overhead would unreasonably complicate a calculator and I hope that supplying written guidelines will be sufficient.

6.A.1   Session and Projects

Every observing session has some time at the start when the telescope needs to be prepared for the upcoming observations. If the previous observer has been using the same setup, then this part of the overhead can be quite short. We suggest observers use 10 min per observing session as a general estimate.

However, most observers may not know the number of observing sessions their project will be split into. The DSS simulations are suggesting that 3 hours is probably the most efficient session size. Thus, observers can approximate the number of sessions they will be scheduled for by dividing the total time they need by 3 hours.

6.A.2   Move Times

Projects that observe many sources may need to estimate the overhead that will be required to slew from source to source. Slew times are given with enough accuracy by equation 4-3. For complicated source lists, I suggest that observers use the 'cleo scheduler' tool to provide average move times and develop an efficient strategy for ordering observations.

6.A.3   Frequency-Switched Observations

One of the inherent advantages of frequency switching is that it, by itself, incurs no extra overhead. Thus, the only overhead one needs to consider is any other observing infrastructure (pointing, calibration, session start-up, etc.).

6.A.1   Position-Switched Observations

The overhead associated with position-switched observations is the move time between the signal and reference positions.   Since the typical reference position is within 1° of the signal position, it is safe to use 15 seconds as the time needed for a move. The half-cycle time for a position switched observation is usually between 5 and 10 minutes, giving fractional overheads on the order of 2 to 5%.

6.A.2   Nodding and Subreflector Nodding Observations

Standard nodding uses the main drives of the telescope to move the source between the two beams of the telescope. Even such a small move of the telescope requires 15 seconds of overhead. Typically, observers use either a 1 or 2-minute half-cycle time for such observations.   Thus, the fractional overhead is usually either 25% or 13%.

Subreflector nodding uses the subreflector to steer the source between the two beams of the telescope and has the advantage of faster switching for better baselines. The subreflector move times are on the order of 1.5 sec so short cycle times incur high overheads.   The suggested half-cycle time for the best baselines is 4.5 seconds, giving a fractional overhead of 33%. If baselines are not too much of an issue, than cycle times can be as long as 30 seconds, with a fractional overhead of 5%.

6.A.3   Zpectrometer Observations

Zpectrometer observations use subreflector nodding with the shortest possible cycle times, and also require observing a blank patch of sky for an equal amount of time as the object of interest.   This leads to a minimum overhead of 66%, plus whatever is needed for pointing and calibration.

6.A.4   Mapping

The overhead within a map, including the time needed for reference observations and the move to a reference position, is already part of the time estimate that the mapping calculator produces. This is true regardless of the selected observing mode. Thus, the only overhead one needs to consider is not related to the maps themselves but to the observing infrastructure (pointing, calibration, session start-up, etc.) that must accompany the maps.

6.A.5   Pointing and Focus Checks

Although the actual cadence of pointing and focus checks depends upon the actual conditions during a run, for the purposes of calculating overhead I suggest using the following table:

Frequency	Suggstion
< 1 GHz	Point only, once per observing session
1 to 3 GHz	Point & Focus once per observing session
3-8 GHz	Point & Focus at start of observing session and then every 3 hrs
8-15 GHz	Point & Focus at start of observing session and then every 1.5 hrs
15-50 GHz	Point & Focus at start of observing session and then every 0.75 hrs

The time needed to perform a pointing check, including the typical move time to a nearby source, is 5 minutes. Adding a focus check adds another minute of overhead. See §6.A.1 for how one can estimate the number and length of sessions.

6.A.1 Calibration (SCAL) measurements

If one desires calibration to better than 10%, we suggest observers perform calibration tests. The suggested way to accomplish this is to observe a strong point-like calibrator using the same hardware and techniques used for their source of interest. Observers who want the best accuracy may want to calibrate every session, otherwise once to three times per project is usually sufficient.

Since the source used will be relatively strong, one requires just a few minutes of observing time. The overhead should also include a typical slew and a preliminary pointing and maybe focus checks. All told, observers should allow 15 min for each calibration observation.

6.A.2 Auto-Out-Of-Focus Holography (AutoOOF)

Out-Of-Focus Holography measures and then tweaks the surface of the antenna to compensate for thermal deformations. It is an important part of all day-time observations when observing above about 27 GHz. We also recommend using the technique a few hours past sunset as the telescope's temperatures will be rapidly changing then. AutoOOF takes about 25 minutes, including all the necessary post overhead of reestablishing the pointing.

For the purpose of estimating overhead, we suggest assuming that AutoOOF will be performed at the start of an observing session and every two hours after that (although one can get away with 3 hours if the sky is overcast.) If observers know that they will be observing at night, then they probably will need at most a single measurement. Thus, to estimate the overhead, one needs to know the expected session length and number of sessions, which can be estimated using the suggestions in §6.A.1.

B.   Pulsar Sensitivity Calculator