TTAT Algorithms v0.2

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Contents

Chapter 1-Introduction

1.1 Updates

- 1.18.22
  - Added Sections 2.1 – 2.2.3
  - Sections need language update (e.g., Target list to Science Target List) – done 2.17.22
- 1.13.22
  - Added Section 6.1
  - Working on Section 6.2.
- 12.14.2021
  - Added Section 3.1
  - Added items to Definitions and Concept List at top of Chapter 3
- 12.10.2021
  - Changed DocumentClass to Report; updated syntax as needed
  - Updated Figure 1.1
- 12.1.2021
  - Moved to Overleaf
  - Folded in "Doodad" document
  - Added concept of Source (defined in Observing Strategy)
  - Changed Target to Science Target; *Target List* to *Science Target List*
  - Added concept of Observing Target, Requested Time, Setup Time, Acquisition Time, Observing Instructions (defined in Calibration Strategy)

1.2 Scope of Document

The intended use of this document is to have a common place to house the information related to the Telescope Time Allocation algorithms. The intended audience is the implementation team and scientists.

1.3 Related Documents

1.4 Overview: Concepts Upstream of the Algorithms

The *Capability Parameter Specifications* are provided by a TTA Group member that specifies the parameters that make up a *Capability* for a *Solicitation.* 688-TTAT-004-MGMT System Description v3.0 Section 3.1 and Table 2 define the grouping of *Capability Parameter Specifications* as

- FIELD SOURCE
- SPECTRAL SPECIFICATION
- PERFORMANCE PARAMETERS
- CALIBRATION PARAMETERS

Tables 1.1, 1.2, and 1.3 overview the groups of *Capability Parameter Specifications* per *Capability.* The *Capability Request Parameters* are then the user's response to the *Capability Parameter Specifications*, and they provide the user supplied information about the requested observations.

The *Capability Request* is composed of the *Capability Request Parameters*, and within a single *Capability Request*, there can be multiple FIELD SOURCES and SPECTRAL SPECIFICATIONS. Generally, a single set of PERFORMANCE PARAMETERS and CALIBRATION PARAMETERS can define any one *Capability Request.* The RMS Sensitivity can be specified for each FIELD SOURCE + SPECTRAL SPECIFICATION pair in the 'Advanced' options of the UI. Table 2 of 688-TTAT-004-MGMT System Description v3.0 provides addition information on the multiplicity of the *Capability Parameter Specifications.*

The *Capability Request* is passed downstream to the algorithm to construct the *Observation Specification.* The remainder of this document provides the details of the algorithms needed to create the *Observation Specification.* Figure 1.1 shows a simple diagram of the algorithms utilized to transform the *Capability Request* into an *Observation Specification.*

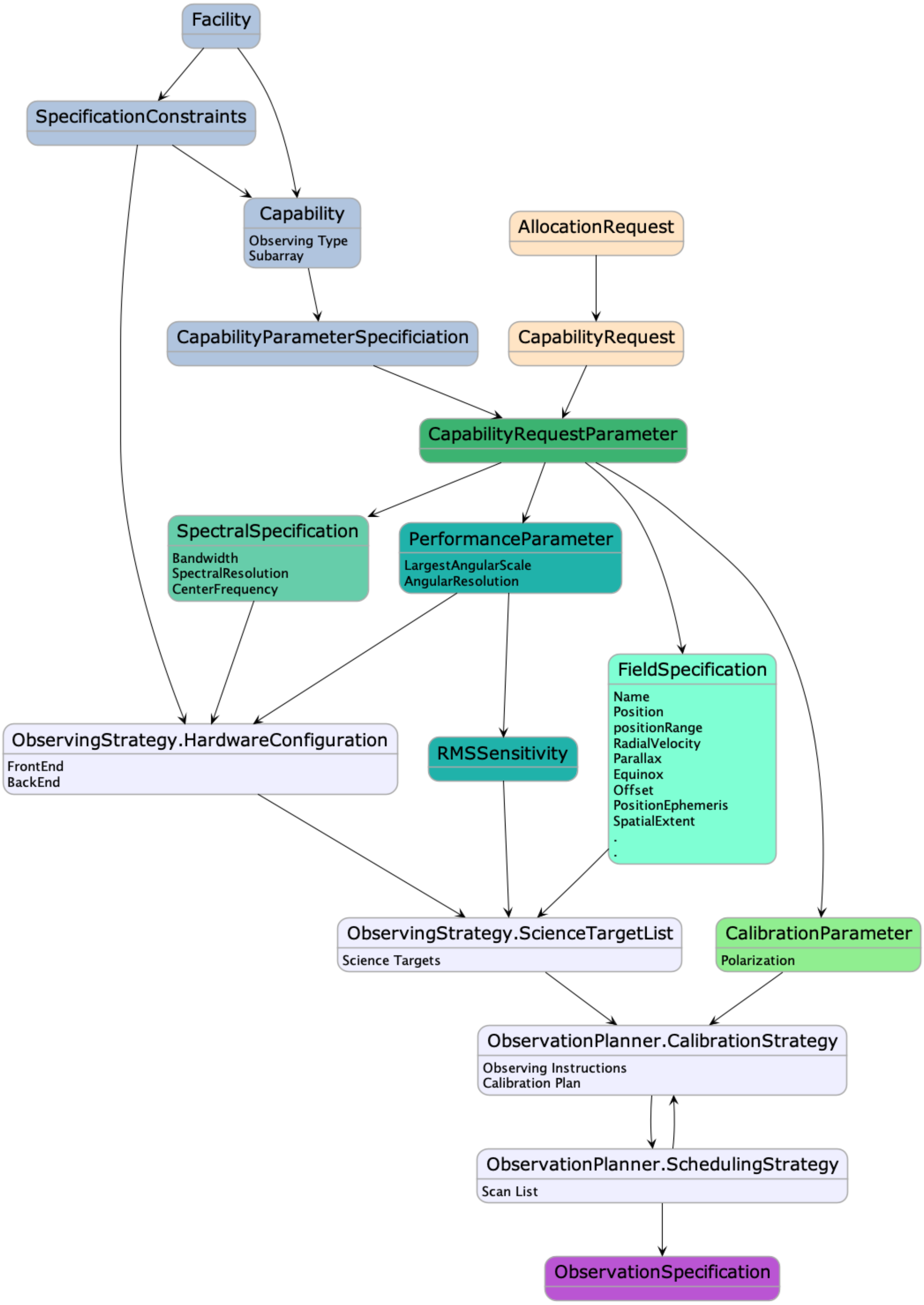


Figure 1.1: Simple diagram to illustrate the relationships between the *Capability Request Parameters*, which are shown in shades of green, and the algorithm (Services; shown in lavender). The algorithm constructs the *Observation Specification* (dark purple), by folding in the *Facility* specific information, which includes the *Capability* (light blue) and the *Specification Constraints*.

Table 1.1: *Capability Parameter Specification*: FIELD SOURCE per *Capability*

Capability Parameter Specification	Example	VLA Continuum	VLA Spectral Line	GBT Continuum	...
Name[a] (str)	3C286	✓	✓	✓	...
Coordinate System (str)	FK5	✓	✓	✓	...
Equinox (str)	J2000	✓	✓	✓	...
Position (float)	(α, δ) = (02:28:30.87, +19:20:45.53) (ℓ,b) = (152.3754°, -37.9133°)	✓	✓	✓	...
Position Uncertainty (float)		✓	✓	✓	...
Field of View (float)	1 sq deg	✓	✓	✓	...
Radial Velocity (float)	837 km s^{-1}	✓	✓	✓	...
Velocity Reference Frame	LSRK	✓	✓	✓	...
Doppler Type	Radio	✓	✓	✓	...
Parallax (float)	1mas	✓	✓	✓	...
Proper Motion	1mas/yr	✓	✓	✓	...
Peak Continuum Flux Density per Synthesized Beam	5 mJy	✓	✓	✓	...
Peak Line Flux Density per Synthesized Beam	1 mJy		✓		...
⋮	⋮	⋮	⋮	⋮	...

[a] This parameter can be any user supplied string. The naming convention is for the ease of identification for the user; it will be propagated to the *Observation Specification* for identification purposes only.

Table 1.2: *Capability Parameter Specification*: SPECTRAL SPEC per *Capability*

Capability Parameter Specification	Example	VLA Continuum	VLA Spectral Line	GBT Continuum	...
Name[a] (str)	C-band	✓	✓	✓	...
Center Frequency (float)	5 GHz	✓	✓	✓	...
Bandwidth (float)	2.048 GHz	✓	✓	✓	...
Spectral Resolution (float)	1.5 kHz	✓	✓	✓	...

[a] This parameter can be any user supplied string.

Table 1.3: *Capability Parameter Specifications* per *Capability*

Capability Parameter Specification	Example	VLA Continuum	VLA Spectral Line	GBT Continuum	...
PERFORMANCE PARAMETERS					
Largest Angular Scale (float)	10″	✓	✓		...
Angular Resolution (float)	0.5″	✓	✓	✓	...
RMS Sensitivity (float)	5.0 μJy bm^{-1}	✓	✓	✓	...
CALIBRATION PARAMETERS					
Flux Density (boolean)	yes/no	✓	✓	✓	...
Test Source (boolean)	yes/no			✓	...
Polarization (boolean)	yes/no	✓	✓	✓	...

Chapter 2-Observing Strategy

Overview – The *Observing Strategy* algorithm decides how to observe a *field source* and translates the *Capability Request* to a *Science Target List*. The details of how to observe a Science Target require knowledge of the Hardware Configuration, the Pointing Pattern, and the Requested Time. The *Science Target List* is passed downstream to the Observation Planner.

Definitions and Concepts –

- The Hardware Configuration describes the FRONT-END and BACK-END of a *Facility* that best suits the requested SPECTRAL SPECIFICATION and PERFORMANCE PARAMETERS of the *Capability Request Parameters*.
- A Pointing Pattern describes the trajectory of an antenna over the course of an observation of a FIELD SOURCE. Pointing Patterns are *Facility* dependent.
- A Source is derived from a FIELD SOURCE or created for a Calibrator. A Source is a normalized data structure that has
  - a name,
  - a Pointing Pattern,
  - a nominal position from the Pointing Pattern.
- The Requested Time is an initial approximation of the time spent by the antenna(s) collecting data that accounts for the requested RMS Sensitivity, the Pointing Pattern, and additional considerations (Section 5.1.3).

The *Observing Strategy* algorithm generates a normalized data structure called the *Science Target List*, which contains the fundamental user request. The *Science Target List* consists of rows of *Science Targets*, which have

- a Source;
- a Hardware Configuration;
- a VLA configuration, if applicable;
- the Requested Time;
- a Repeat Count, if applicable.

Note, a Science Target is not a Calibrator. The *Science Target List* is passed downstream to the *Observation Planner*.

Table 2.1: VLA Receivers and BACK-ENDS: capabilityConfig.json

here's a test table

2.1 VLA Observing Strategy

Inputs and parameters for the VLA *Observing Strategy*:

1. *Capability Request Parameters*
   (a) Column 3 of Tables 1.1, 1.2, and 1.3
2. *Capability*
   (a) Table 2.1
3. *Specification Constraints*
   (a) Diameter of Antenna Dish (D_{dish}; m)
   (b) Illumination Taper Edge (T_e; dB)
   (c) Settle Time (s)

2.1.1 VLA Hardware Configuration

The VLA Hardware Configuration algorithm selects the FONT-END and the BACK-END that best matches the *Capability Request Parameters*. The FONT-END consists of a Receiver and VLA Configuration. An outline of the algorithm is shown in Figure 2.1.

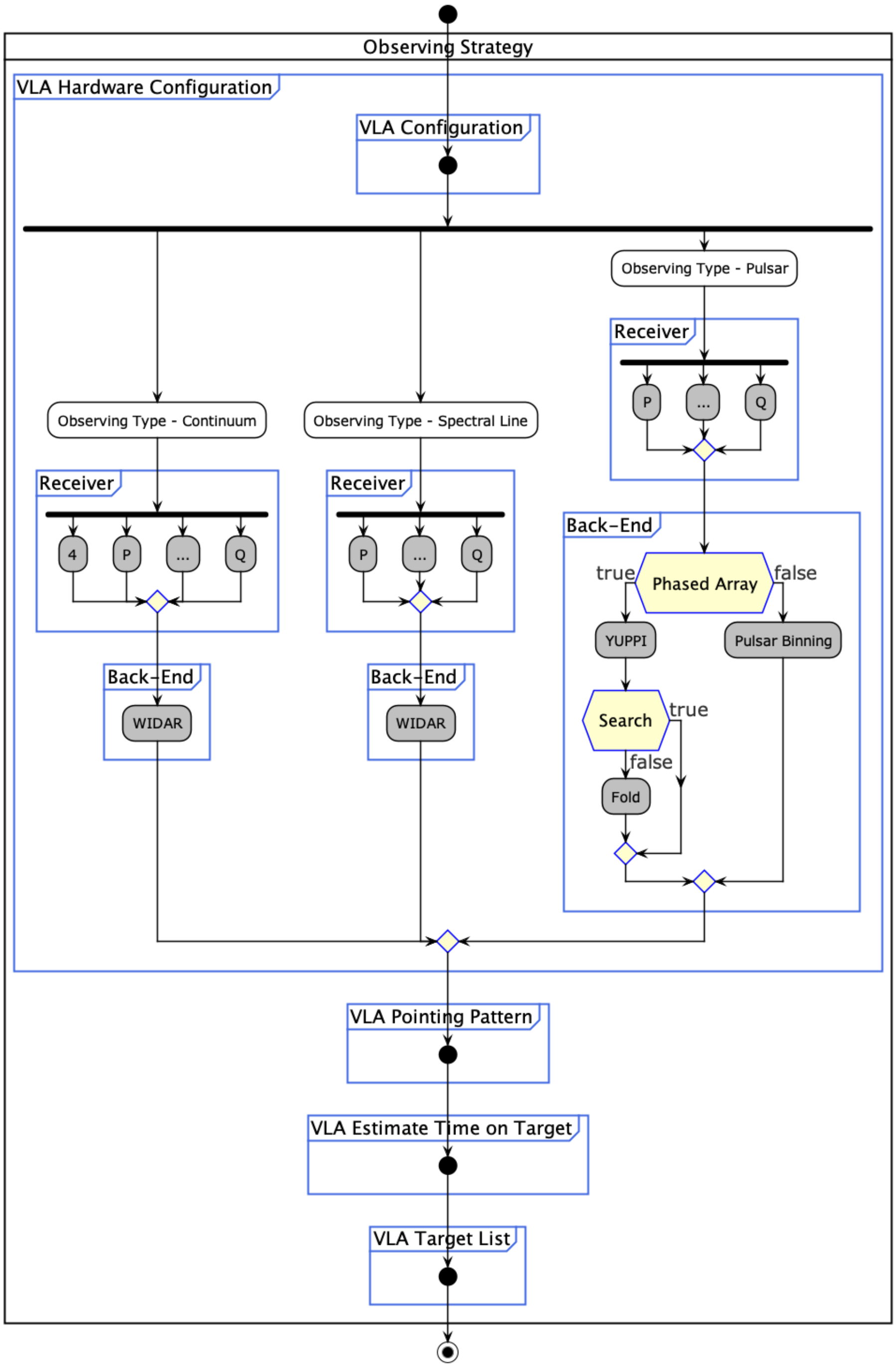


Figure 2.1: Diagram of algorithm to select the FRONT-END for the VLA, which includes the Array Configuration and the Receiver, and the BACK-END.

2.1.1.1 Algorithm: Selection of VLA Configuration

- PLACEHOLDER: Algorithm

2.1.1.2 Algorithm: Selection of VLA Receiver

- PLACEHOLDER: Algorithm

2.1.1.3 Algorithm: Selection of VLA back-end

- PLACEHOLDER: Algorithm

2.1.2 VLA Pointing Patterns

Each *Capability Request* will call the VLA Pointing Pattern to determine which Pointing Pattern is needed, regardless of *Observing Type*. The VLA patterns include the following:

$$\text{VLA Pointing Patterns} \begin{cases} \text{Single Pointing} \\ \\ \text{Mosaic} \begin{cases} \text{On-the-Fly} \\ \text{Discrete} \begin{cases} \text{Hexagonal} \end{cases} \end{cases} \end{cases}$$

The following outlines the steps needed to determine which Pointing Pattern to employ, which is diagrammed in Figure 2.2.

1. The qualitative condition for a Single Pointing pattern is when the Primary Beam, θ_{PB}, is much greater than Ω_{FOV}:
$$\theta_{\text{PB}} > \text{scalar} \times \ max(\Omega_{\text{FOV}}), \tag{2.1.1}$$
where scalar = XX, and the Primary Beam is compared to the largest dimension of Ω_{FOV}. The Primary Beam of the telescope is
$$\theta_{\text{PB}} = (1.02 + 0.0135\,T_e) \times \frac{c}{\nu} \times \frac{1}{\text{D}_{\text{dish}}} \text{ rad,} \tag{2.1.2}$$
or
$$\theta_{\text{PB}} = 1.25\frac{c}{\nu} \times \frac{1}{\text{D}_{\text{dish}}} \text{ rad}$$
where c is the speed of light in m s^{-1}, $\nu = \nu_c + \Delta\nu$ is the upper frequency (Hz) of the requested bandwidth.

2. If Eq (2.1.1) is True, the Single Pointing pattern is used (go to Section 2.1.2.1).

3. If False, then a mosaic pattern is used, which is either a discrete mosaic or an On-the-Fly (OTF) mapping.

   (a) The algorithm decides between OTF mapping and a discrete mosaic based on two conditions:

      i. *Overhead.* When the Settle Time of the telescope is comparable to the Effective Integration Time, t_{eff}, the overhead becomes large or
      $$t_{eff} < XX\text{s.} \tag{2.1.3}$$

      ii. *Data Rate.* The Data Rate for OTF mapping must be less than XX.

   (b) If either condition is False, a discrete mosaic pattern is used (go to Section 2.1.2.2).

   (c) If both conditions are True, OTF mapping is used (go to Section 2.1.2.3).

Text in Figure 2.2	Condition	Reference in Text
(1) Condition for Single Pointing	$\theta_{\rm PB} >$ scalar $\times$ $max(\Omega_{\rm FOV})$	§2.1.2
(2) Condition for OTF	t_{eff} < XX s AND Data Rate < XX	§2.1.2
(3) Validate OTF RA Spatial Extent	$\Omega_{\rm RA} >$ XX	§2.1.2.3
(4) Validate *scan rate*	*scan rate* < 3 arcmin s^{-1}	§2.1.2.3
(5) Validate Dump Time	$t_{\rm dump} < 0.6$ s	§2.1.2.3

2.1.2.1 VLA Single Pointing

The parameters needed to describe a VLA Single Pointing Pattern are as follows:

1. Position, which is equivalent to the FIELD SOURCE: Position.
2. Requested Time

2.1.2.2 VLA Discrete Mosaic

The recommended discrete mosaic pattern for the VLA is a Hexagonal Pattern. The parameters needed to fully describe a Discrete Mosaic Pattern are the following:

1. Position Per Pointing – For each pointing, this is a coordinate that tells an antenna where to point. The nominal position of the pointing pattern is equivalent to theFIELD SOURCE: Position.

2. Requested Time Per Pointing – The time an antenna spends collecting data per pointing. This does not include overhead.

The Hexagonal Pattern is composed of a number of pointings along a line of constant Declination (called a row) to span the angular extent in RA ($\Omega_{\rm RA}$). The angular extent in Dec ($\Omega_{\rm Dec}$) is spanned by layering rows. The pattern, which includes the Position Per Pointing and the Requested Time Per Pointing, is constructed with the following steps.

1. The center of the mosaic is equal to the Position in the FIELD SOURCE. Once specified, the Position Per Pointing is calculated following the guidelines below.

   (a) The number of pointings needed to span the requested angular extent in RA ($\Omega_{\rm RA}$) and that in Dec ($\Omega_{\rm Dec}$) are

$$n_{\rm ra} = \frac{\Omega_{\rm RA}}{\theta_{hex}} \text{ and}$$

$$n_{\rm dec} = \frac{\Omega_{\rm Dec}}{\theta_{row}},$$

   respectively, rounded up to the nearest integer. $\theta_{\rm hex}$ and $\theta_{\rm row}$ are defined as

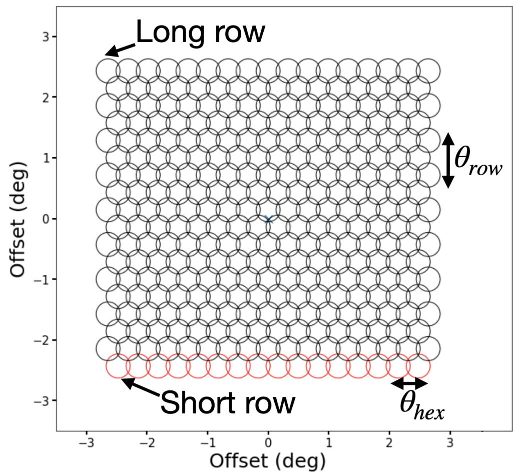


Figure 2.3: Example of a VLA Hexagonal Pointing Pattern. The variables, terms, and circles in red are described in the text.

   i. The angular spacing along the rows of the mosaic is

$$\theta_{\rm hex} = \frac{\theta_{\rm PB}}{\rm scalar},$$

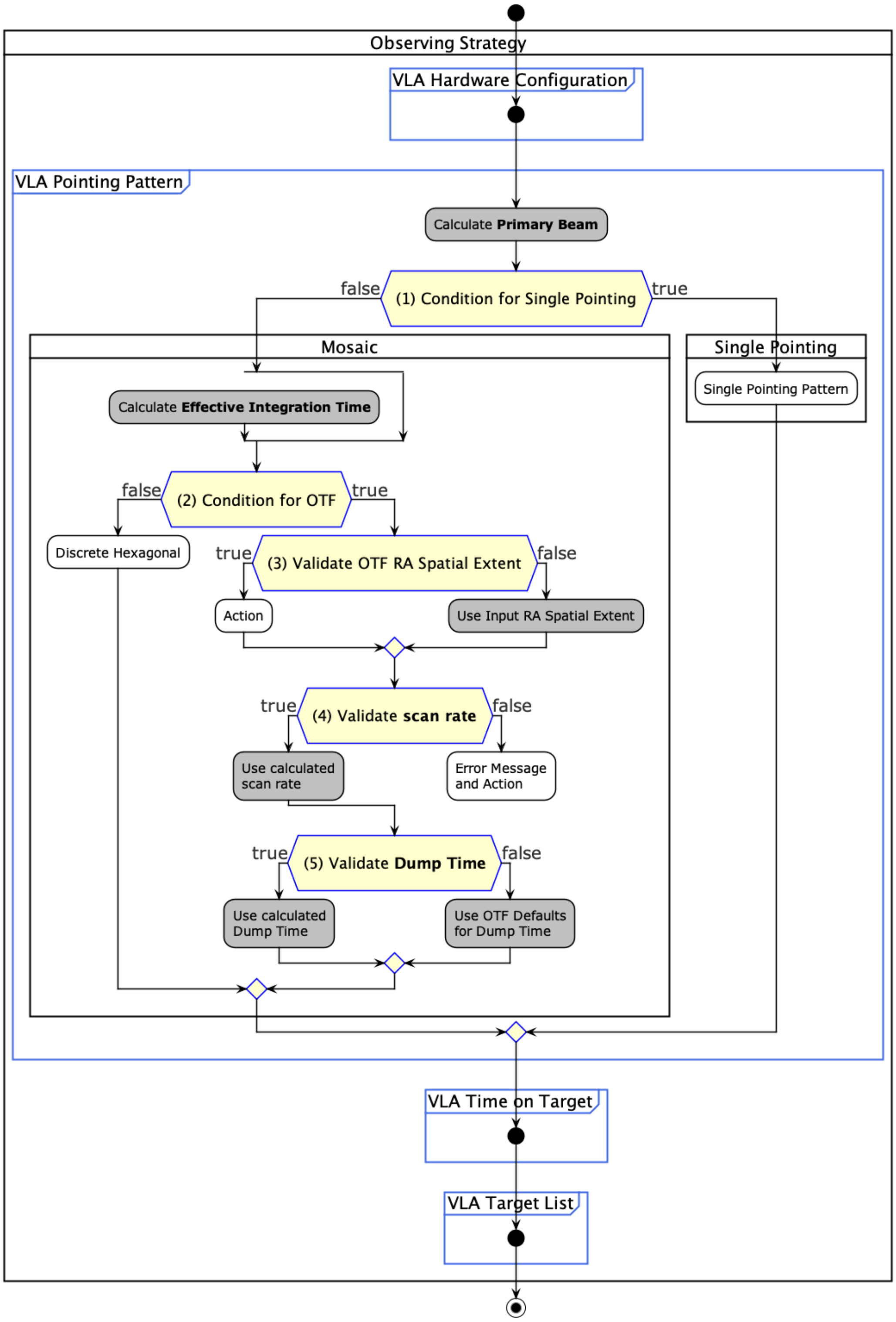


Figure 2.2: VLA *Observing Strategy*

where

$$\text{scalar} = \begin{cases} 1.2 \text{ (Nyquist)} \\ \sqrt{2} \\ \sqrt{3}, \end{cases}$$

and the upper frequency $(\nu_c + \Delta\nu/2)$ of the requested bandwidth is used to calculate the Primary Beam, $\theta_{\rm PB}$. The algorithm uses scalar = XX by default.

ii. The angular spacing between the rows of the mosaic

$$\theta_{\text{row}} = \left(\frac{3}{2}\right)\theta_{\text{hex}}.$$

(b) The pattern is constructed by alternating rows of different lengths, called short rows and long rows. The rows are offset in Declination by θ_{row}. An example of a short row is highlighted in red in Figure 2.3.

(c) TODO – Someone probably has a better way on implementing the pattern than my code does. Have at. Here are the rules though:

i. Long rows consist of n_{ra}+1 pointings, each pointing offset in RA by θ_{hex}.

ii. Short rows consist of n_{ra} pointings, each pointing offset in RA by θ_{hex}.

iii. The long and short rows are offset from each other in RA by $\pm\frac{1}{2}\theta_{hex}$ to stagger position of each pointing between the rows, which creates the hexagonal pattern.

2. Each pointing will have the same integration time, so the Requested Time Per Pointing is calculated as follows.

(a) Use the VLA Sensitivity Calculator (§5.1.2.1) to determine the Effective Integration Time, t_{eff}.

(b) The Requested Time Per Pointing is

$$\text{Requested Time Per Pointing} = \frac{t_{eff}}{n_{tot}},$$

where n_{tot} is the total number of pointings in the mosaic given by

$$n_{tot} = n_{\text{dec}} \times (n_{\text{ra}} + \frac{1}{2}),$$

rounded up to the nearest integer.

3. The additional parameters that are included in the *Observation Specification* for reporting purposes are

(a) Mosaic Beam Area:

$$\Omega_{beam} = 0.5665\ \theta_{\text{PB}}^2 \tag{2.1.4}$$

(b) Requested Time (no overhead):

$$\text{Requested Time} = n_{tot} \times \text{Requested Time Per Pointing} \tag{2.1.5}$$

(c) Survey Speed:

$$\text{Survey Speed} = \frac{\Omega_{beam}}{t_{eff}} \tag{2.1.6}$$

4. Scheduling Notes:

(a) The observing order is established in the *Scheduling Strategy.*

2.1.2.3 VLA OTF

An On-the-Fly mosaic scans the sky in rows (stripes) along a line of constant Declination. The telescope scans continuously along a row (e.g., east-west) and then scans the opposite direction in the next row, which is offset in Declination from the preceding row. To fully describe an OTF pattern, the following parameters are needed:

1. Positions of the first and last pointings of each row.

2. Time Per Row – This is the time interval an antenna collects data for a row; this does not include overhead.

The pattern is constructed with the following steps.

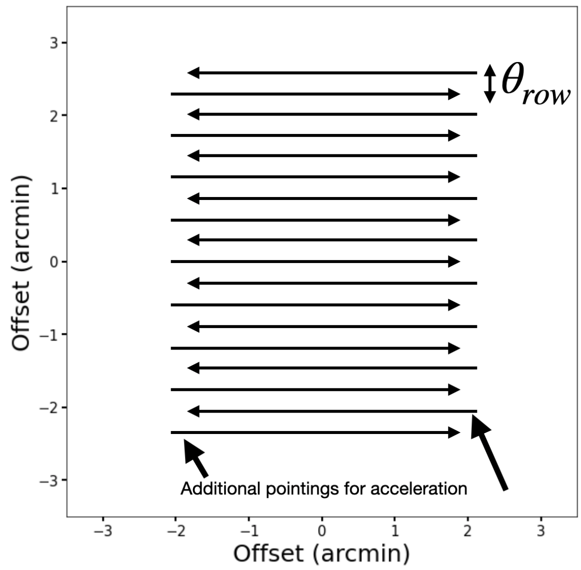


Figure 2.4: Example of VLA OTF mapping for a small Ω_{ra}. The offset in Dec is equal to θ_{row}.

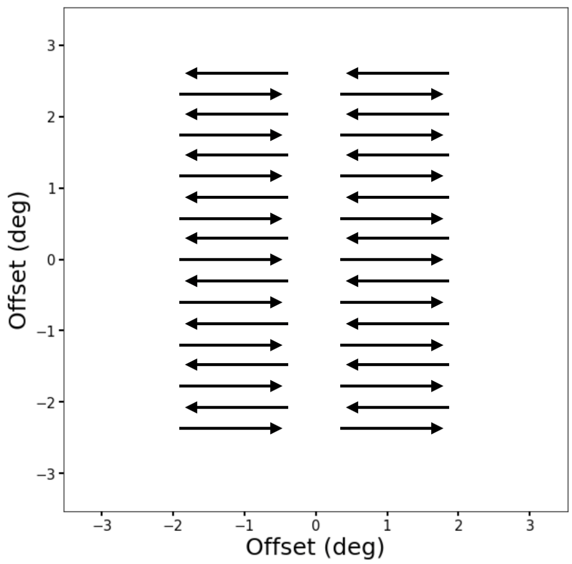


Figure 2.5: Example of VLA OTF mapping for a large Ω_{ra}. The offset in RA between the tracks is artificially inflated. The offset in Dec is between rows is equal to θ_{row}.

1. If the angular extent in RA, $\Omega_{\rm ra}$, is too large, the length of the rows is reduced to maintain flexibility for dynamic scheduling due to elevation concerns. To facilitate the requested coverage by $\Omega_{\rm ra}$, multiple OTF patterns are constructed instead of a single OTF pattern. In a sub-pattern, all the rows needed to span the requested angular extent in Declination are observed beFigures 2.4 and 2.5 show examples of OTF pointings for a small and large angular extent, respectively. The condition for splitting up the OTF pattern is when

$$\Omega_{\rm RA} \ > \ XX, \qquad (2.1.7)$$

the algorithm constructs N contiguous OTF sub-patterns with a width of $\Delta_{RA} \sim$ XX, where

$$\Omega_{\rm RA} = \sum_{i=1}^{N} \Delta_{\rm RA,i}.$$

   (a) If this condition is met, $\Delta_{\rm RA}$ should be used in place of $\Omega_{\rm RA}$ in Steps 2f, 3a, and 3b.

2. The Time Per Row is the time the antenna spends collecting data along a row. It does not include the slew and settle time. It is calculated in the steps below.

   (a) The *scan rate* is how quickly an antenna will slew across the sky and is given by

$$scan\ rate = \frac{[0.5665\ \theta_{\rm PB}^2]}{t_{eff} \times \theta_{\rm row}}. \qquad (2.1.8)$$

   The quantity in the square brackets is the beam area, which uses the upper frequency of the requested bandwidth ($\nu_c + \Delta\nu/2$) to calculate Primary Beam, $\theta_{\rm PB}$. The Effective Integration Time is t$_{eff}$ (see Section 5.1.2.1), and $\theta_{\rm row}$ is the angular spacing between rows (stripes):

$$\theta_{\rm row} = \frac{\theta_{\rm PB}}{\rm scalar}, \text{ where}$$

$$\text{scalar} = \begin{cases} \sqrt{2} \\ \sqrt{3} \\ 4, \end{cases}$$

where the default value used by the algorithm is XX.

(b) The algorithm performs a check on the value of the *scan rate*.

i. If the *scan rate* is greater than 3 ? 10 arcmin s^{-1}, the algorithm will provide a message to the user prompting an Action.

ii. E.g., The message instructs the user to change the requested RMS Sensitivity, the frequency, or bandwidth OR defaults to the value of XX. Figure 2.6 illustrates the relationship between t_{eff}, θ_{PB}, and the *scan rate*.

(c) In OTF mapping, the integration time is inherently fast and will effectively function as a Dump Time (t_{dump}), which is the time interval in which the data is processed by the backend processing cluster. To prevent beam smearing, at least 10 integrations are needed as the antenna scans a distance equal to the FWHM of the Primary Beam. The calculated Dump Time, t_{dump}, for OTF mapping is

$$t_{\mathrm{dump}} \sim 0.1 \ \times \ \frac{\theta_{\mathrm{PB}}}{scan\ rate}. \tag{2.1.9}$$

(d) The algorithm performs a check of value of t_{dump}, as the phasecenter cannot change faster than 0.6 ? 0.5s.

i. If $t_{dump} < 1$s for 8-bit observing, the default Dump Time, $t_{dump,default}$, of 1s is used.

ii. If $t_{dump} < 4$s for 3-bit observing, $t_{dump,default} = 4$s.

(e) If the defaults are used for t_{dump}, the Number Of Integrations Per Phasecenter, n_{integ}, is

$$n_{integ} = \frac{t_{dump,default}}{t_{\mathrm{dump}}}, \tag{2.1.10}$$

otherwise, $n_{integ} = 1$.

(f) The number of pointings in a row (stripe) is

$$n_{\mathrm{stripe}} = \frac{\Omega_{ra}}{[scan\ rate\ \times\ n_{integ} \times t_{dump}]} \tag{2.1.11}$$

where the quantity in the square brackets is the angular distance between two phasecenters, θ_{point}.

(g) The Time Per Row is then

$$\text{Row Duration} = (n_{stripe} + 1) \times n_{integ} \ \times \ t_{dump}. \tag{2.1.12}$$

The addition of 1 to n_{stripe} is to allow the antenna(s) time to accelerate.

3. The center of the OTF pattern is equal to the Position specified in FIELD SOURCE. The starting row is the southern most one (Row 0), and is observed east to west. There are n_{rows} in the pattern, so the last row is number Row n_{rows} - 1. Additionally, an extra phasecenter is added to the start of each row to allow for the telescope to accelerate.

(a) For Row 0, the Positions of the first and last pointings of the row are given by

$$(\alpha_{start,0}, \delta_{start,0}) = (\alpha_{position} + \frac{\Omega_{\mathrm{RA}}}{2} + \theta_{point},\ \delta_{position} - \frac{\Omega_{\mathrm{Dec}}}{2})$$

and

$$(\alpha_{stop,0}, \delta_{stop,0}) = (\alpha_{position} - \frac{\Omega_{\mathrm{RA}}}{2}, \delta_{start,0}).$$

(b) Then, the odd rows, which are observed west-to-east, have positions of

$$(\alpha_{start,n}, \delta_{start,n}) = (\alpha_{position} - \frac{\Omega_{\mathrm{RA}}}{2} - \theta_{point},\ \delta_{start,n-1} + \theta_{row})$$

and

$$(\alpha_{stop,n}, \delta_{stop,n}) = (\alpha_{position} - \frac{\Omega_{\mathrm{RA}}}{2},\ \delta_{start,n})$$

and the even numbered rows, which are observed east-to-west, have start and stop positions of

$$(\alpha_{start,n}, \delta_{start,n}) = (\alpha_{position} + \frac{\Omega_{\mathrm{RA}}}{2} + \theta_{point},\ \delta_{position} - \frac{\Omega_{\mathrm{Dec}}}{2} + \theta_{row})$$

and

$$(\alpha_{stop,n}, \delta_{stop,n}) = (\alpha_{position} - \frac{\Omega_{\mathrm{RA}}}{2},\ \delta_{start,n})$$

until $n = n_{rows}$-1, where

$$n_{rows} = \frac{\Omega_{\mathrm{Dec}}}{\theta_{row}}$$

and is the number of rows required to span Ω_{Dec}.

4. There are additional parameters that the User will want displayed, that are useful for validation purposes, or may need to be accessible to other portions of the algorithm.

   (a) Beam Area: Equation 2.1.4

   (b) Survey Speed: Equation 2.1.6

   (c) If Condition 2.1.7 is True, the number of OTF sub-patterns, N, and the extent in RA of each sub-pattern, Δ_{RA}.

   (d) Scan Rate: Equation 2.1.8

   (e) Dump Time + Validation Check: Equation 2.1.9

   (f) Number of Integrations Per Step: Equation 2.1.10

   (g) Requested Time, which does not include overhead:

$$\text{Requested Time} = n_{rows} \times \text{Time Per Row} \tag{2.1.13}$$

5. OTF Scheduling Notes:

   (a) Scans from east to west move with the sidereal motion while scans from west to east are counter-sidereal. Therefore, for the same on-the-sky angular scan rate, the east-to-west scans will require faster telescope motion. Additionally, observing near the Zenith where the azimuthal rate becomes very high should be avoided.

   (b) For OTF targets close to 34 deg Dec, map well before or well after transit, i.e. close to rise or set. `https://science.nrao.edu/facilities/vla/docs/manuals/opt-manual/observation-preparation-tool/scan-modes-obs-modes/on-the-fly-mosaicking`

   (c) The Slew and Settle time needs to be accounted for.

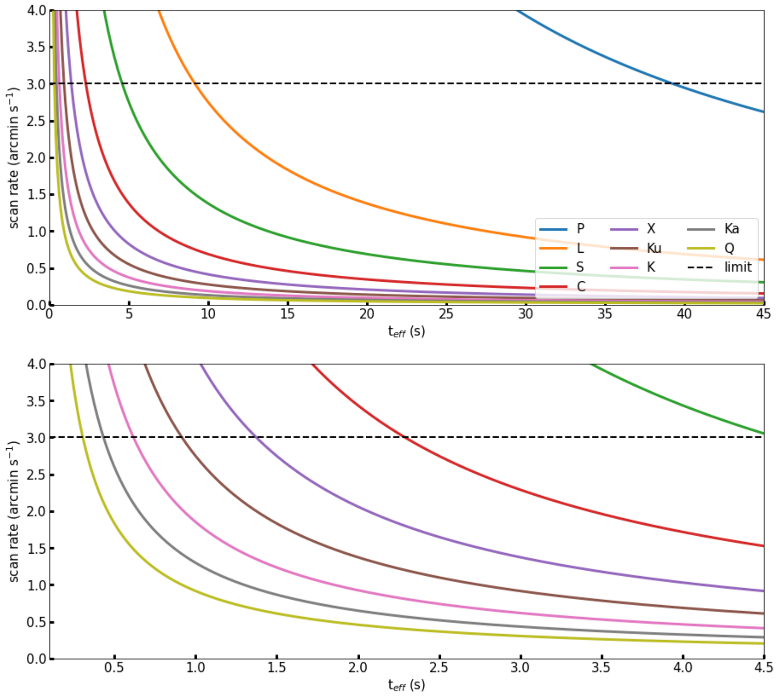


Figure 2.6: *Top.* The *scan rate* as a function of different Effective Integration Times and VLA frequency bands, as represented by the different colored curves. *Bottom.* Same as the top plot except the range of the abscissa is truncated to provide better detail.

2.1.3 VLA Requested Time

RMS sensitivity is not the only concern for time on source. Need to fold in other toggles if applicable. This may not be the best place to do so. Can the Requested Time from the Pointing Pattern be updated here?

1. Look in the System Concept Document for information about this
   (a) uv-coverage for an interferometer
   (b) event occurrence rate
   (c) sensitivity
   (d) "etc"
2. uv-coverage is concern: how to tell the algorithm to observing for e.g., 30 minutes across an 8 hour LST range.
3. Pulsars don't care about RMS (really) but they do want to repeat count at specific times
4. If overhead dominated (rule? for VLA $< 50\%$ for example), then increase integration time. How to get the algorithm to do this.
5. Does there need to be a performance parameters for Dynamic range or Parallactic Angle?

2.1.4 VLA *Science Target List* Generation

The following are the inputs needed to generate the *Science Target List*:

2.2 GBT Observing Strategy

The GBT *Observing Strategy* takes the inputs of

1. *Capability Request Parameters*
   (a) Column 5 of Table **??**
2. *Capability*
   (a) Table 2.2
3. *Specification Constraints*
   (a) Diameter of Antenna Dish (D_{dish}; m)
   (b) Illumination Taper Edge (T_e; dB)
   (c) Settle Time (s)

Table 2.2: GBT Receivers and BACK-ENDS: capabilityConfig.json

here's a test table

2.2.1 GBT Hardware Configuration

An observing type is decided upstream; the available observing types are continuum, spectral line, pulsar, or radar. The algorithm then flows according to the logic shown in Figure 2.7.

2.2.1.1 Algorithm: Selection of GBT Receiver

- PLACEHOLDER: Algorithm

2.2.1.2 Algorithm: Selection of GBT back-end

- PLACEHOLDER: Algorithm

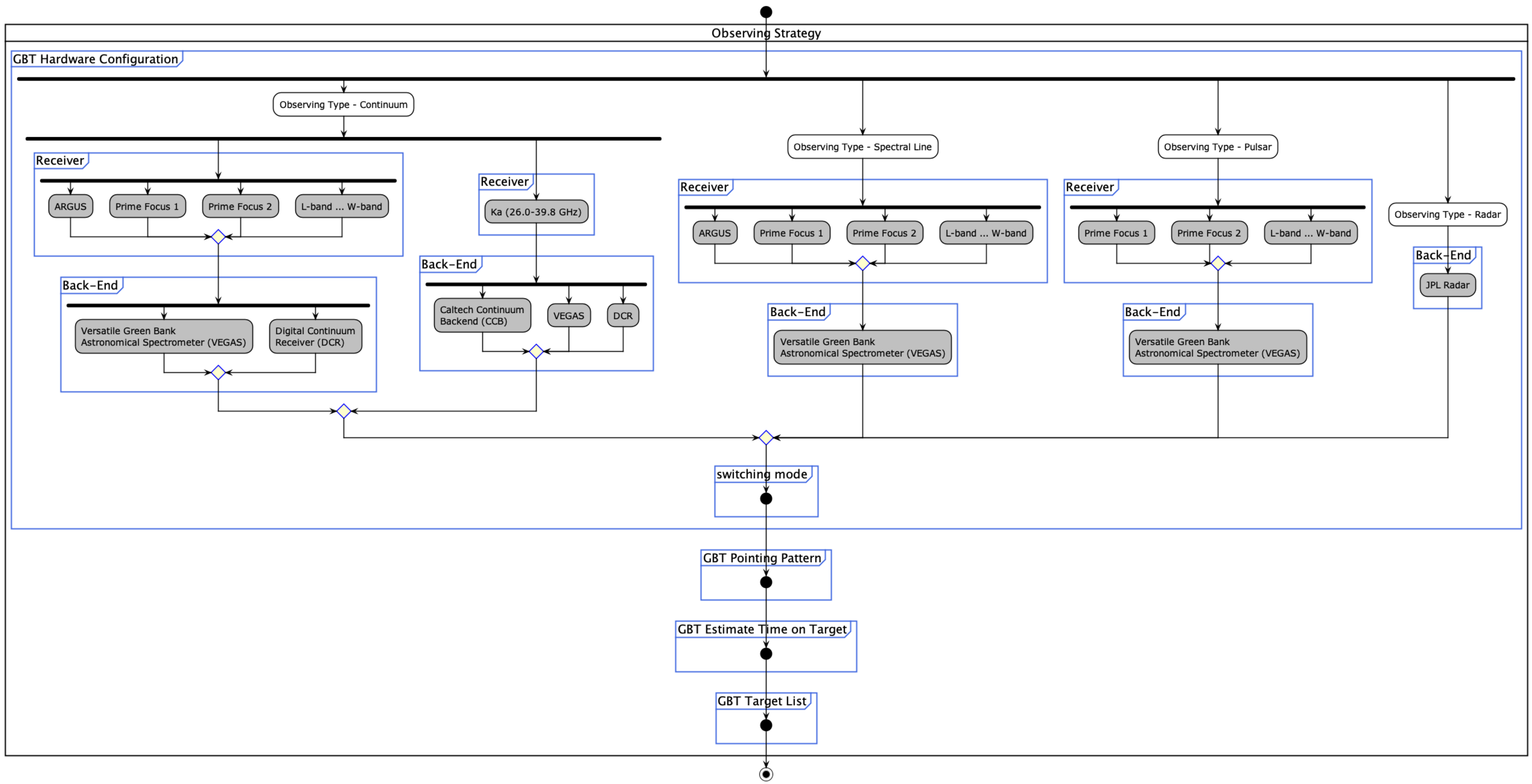


Figure 2.7: Diagram of algorithm to select the FRONT-END for the GBT and the BACK-END.

2.2.1.3 Pointing Patterns for the GBT

Dana: It may not be the best way to say single pointing vs mosaic for the GBT.

The standard Pointing Patterns[1] available to the algorithm for the GBT include the following

$$\text{GBT Pointing Patterns} \begin{cases} \text{Single Pointing} \\ \text{Mosaic} \begin{cases} \text{OTF} \begin{cases} \text{RAlongmap} \\ \text{RAlongmapWithReference} \\ \text{Declatmap} \\ \text{DeclatmapWithReference} \\ \text{Daisy} \end{cases} \\ \text{Discrete} \begin{cases} \text{PointMap} \\ \text{PointMapWithReference} \end{cases} \end{cases} \end{cases}$$

The condition for Single Pointing is when the Primary Beam, θ_{PB}, is much greater than the Field of View. The Primary Beam is compared to the largest dimension of Ω_{FOV}.

$$\theta_{\text{PB}} > \text{scalar} \times \; max(\Omega_{\text{FOV}}), \tag{2.2.1}$$

where scalar = XX. The Primary Beam of the telescope is

$$\theta_{\text{PB}} = (1.02 + 0.0135\, T_e) \times \frac{c}{\nu} \times \frac{1}{\text{D}_{\text{dish}}} \text{ rad,}$$

or

$$\theta_{\text{PB}} = 1.25 \frac{c}{\nu} \times \frac{1}{\text{D}_{\text{dish}}} \text{ rad}$$

where c is the speed of light in m s^{-1}, $\nu = \nu_c + \Delta\nu$ is the highest frequency in Hz. The remaining variables are defined in Section 2.2.

If condition (2.2.1) is not met, i.e., the primary beam is smaller than the Field of View of the source, then a mosaic pattern is considered: a discrete mosaic or OTF mapping. The algorithm decides between OTF mapping and a discrete mosaic based on two conditions.

[1] The GBT Observing Guide (GBTog) calls these Scan Types

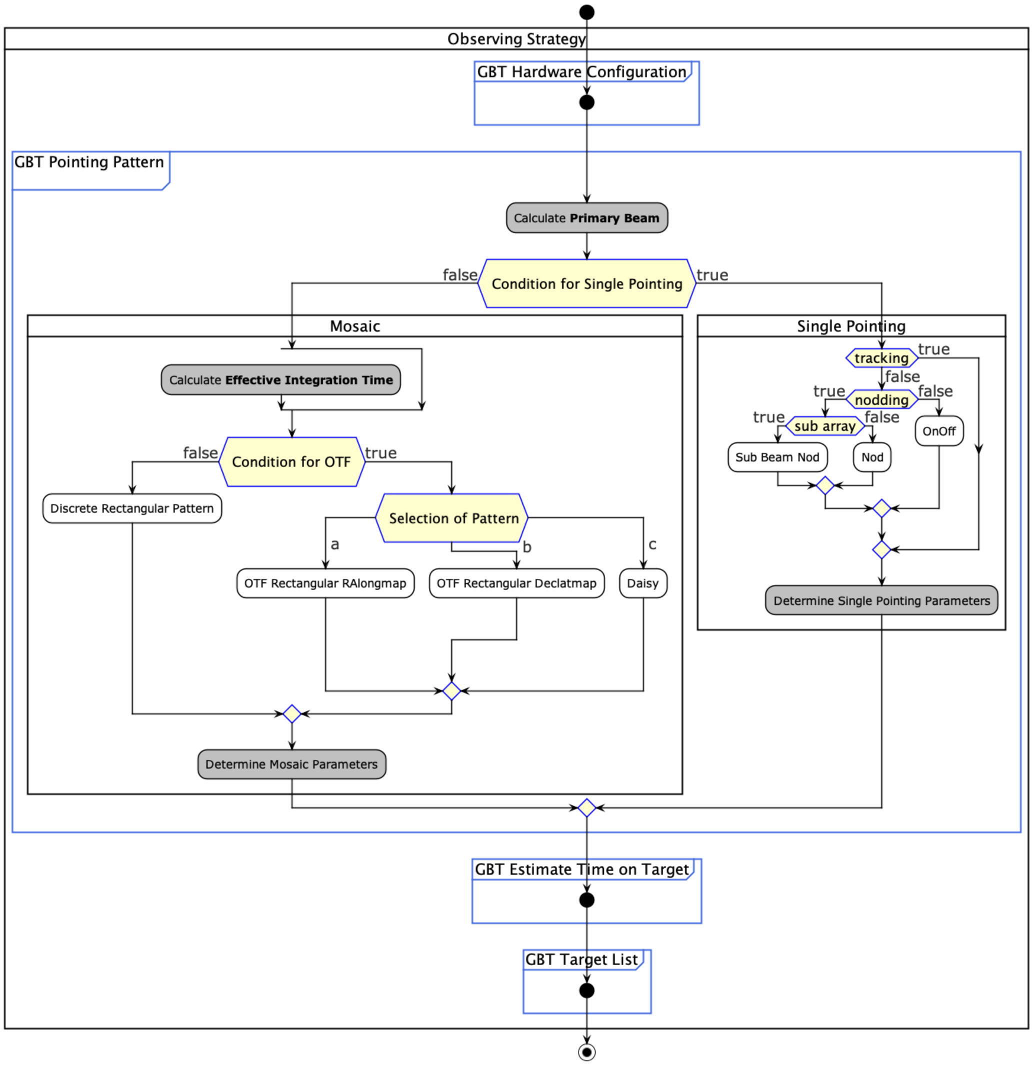


Figure 2.8: GBT *Observing Strategy*

Condition for Figure 2.8		Section
Condition for Single Pointing	$\theta_{\mathrm{PB}} > \text{scalar} \times \ max(\Omega_{\mathrm{FOV}})$	2.2.1.3
Condition for OTF	???	2.2.1.3
Selection of Discrete Pattern	???	2.2.1.3.2
Tracking	???	2.2.1.3.1
Nodding	???	2.2.1.3.1
Sub array	???	2.2.1.3.1

2.2.1.3.1 GBT Single Pointing

High Frequency receivers have two beams. If the source is not extended and doing position switched observations, use Astrid Nod() procedure

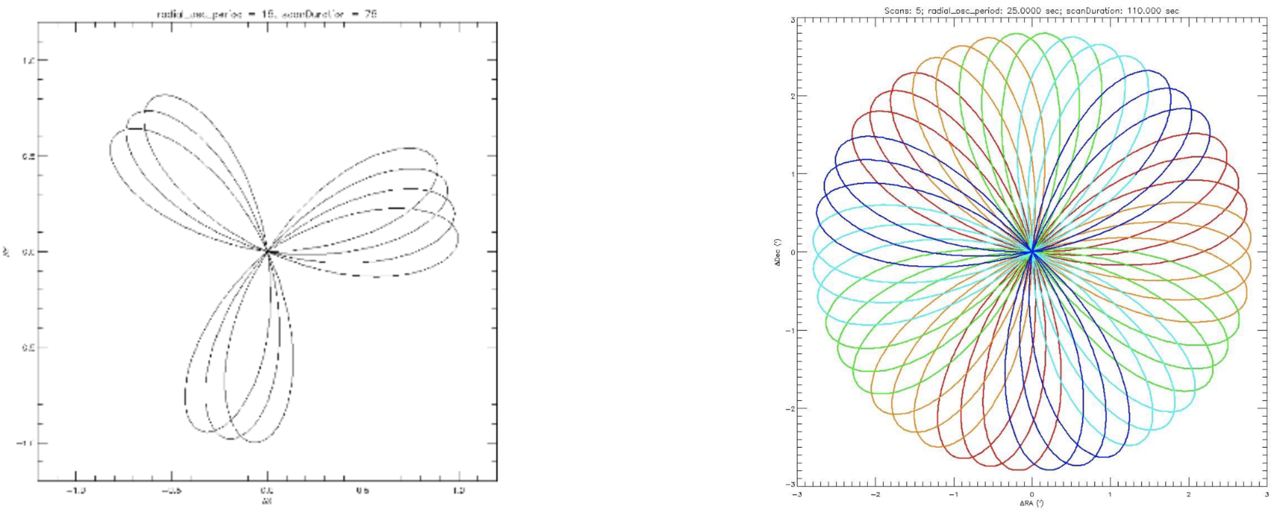
2.2.1.3.2 GBT Discrete Mosaic

2.2.1.3.3 GBT OTF

2.2.1.3.3.1 GBT RAlongmap and Declatmap

2.2.1.3.3.2 GBT Daisy Map

A Daisy map scans continuously around a central point as shown in Figure 2.9. This pattern is discussed in detail in Section 6.4.3.7 of *Observing with the Green Bank Telescope*[2].



(a) (b)

Figure 2.9: GBT Daisy maps at 5 radial oscillations (a) and 22 radial oscillations (b), which is a closed pattern.

[2] `https://science.nrao.edu/facilities/gbt/observing/GBTog.pdf`

2.2.2 GBT Requested Time

1. Spectral lines towards strong continuum sources need careful configuration.
2. weak broad spectral lines (wider than $\sim$ 100 MHz) towards a strong continuum emission (more than 1/10th the system temperature), then need to consider double position switching.
3. need to find proper IF balance – BalanceOnOff() in section 6.4.1

2.2.3 GBT *Science Target List* Generation

Chapter 3-Observation Planner

Overview – The *Observation Planner* algorithm converts the *Science Target List* into the *Observation Specification*. It contains the *Calibration Strategy* and the *Scheduling Strategy*.

Hierarchical Definitions and Concepts –

- Acquisition Time is the time an antenna spends taking data in a Sub-scan;
- Antenna slew time is the time is takes for an antenna to move on the sky between two positions;
- Hardware configuration overhead is the time needed for hardware changes (e.g., changing receivers);
- Settle time is the time an antenna needs to stabilize? after it has moved;
- Setup Time (§ 5.1.1) is the sum of the antenna slew time + settle time + hardware configuration overhead;
- Sub-scan
  - Specification of the shortest, contiguous block of time over which an antenna is taking data. Each Sub-scan consists of
    * a Source;
    * a Hardware Configuration;
    * an Acquisition Time;
    * a Setup Time;
    * an antenna trajectory, as derived upstream by the Pointing Pattern;
    * a scientific intent, which is called a Sub-scan Intent (Table 3.1).
- Sub-scan Prototype
  - A sub-scan that has a Source, a Hardware Configuration, and Sub-scan Intents but does not include an Acquisition Time or a Setup Time.
- Scan Intent
  - A tag that describes the scientific purpose of a set of Sub-scans, e.g., a flux, phase, or bandpass calibration, a pointing, an observation of a Science Target. A single scan can have multiple Scan Intents. See Table 3.1.
- Scan
  - A group of Sub-scans that share Scan Intent. All scans have at least one sub-scan.
- Maximum Duration
  - Maximum length for any single Scan including all associated Setup Times on an Observing Target. The maximum length of time allowed for a Sub-Scan, Scan, all Sub-scans, or all Scans.
- Maximum Acquisition Time

  - The maximum time of any single Scan on an Observing Target

- Requested Time
  - The time specified for a Science Target in the *Science Target List*.

- Science Target Integration Time(s)
  - The sum of the Acquisition Times for all Sub-scans on a Science Target with Sub-scan Intent ON_SOURCE and associated with a Scan Intent of OBSERVE_TARGET. This is greater than or equal to the Requested Time when all these Sub-scans are complete.
  - The sum of all Acquisition Times for all Sub-scans for all Science Targets with Sub-scan Intent ON_SOURCE and associated with a Scan Intent of OBSERVE_TARGET (Scan List level).

- Observing Target
  - The generalization of a Science Target to include Calibrators; it consists of
    * a Hardware Configuration,
    * a Source.
  - All Science Targets are Observing Targets, but not all Observing Targets are Science Targets.

- Time on Observing Target(s)
  - The sum of the Acquisition Times for all Sub-scans on this Observing Target. This can be greater than or equal to the Requested Time for Science Targets; it can be greater than or equal to the Science Target Integration Time.
  - The sum of all Acquisition Times for all Sub-scans for all Observing Targets (Scan List level).

- Duration
  - Generally, a duration is the total time of a Sub-Scan, Scan, all Sub-scans, or all Scans. This includes overheads. Specifically, it is the total time of all Scans, and Duration = Setup Time + Time on Observing Targets.

- Overhead
  - Generally, the overhead is any time an antenna is not collecting data on a Science Target. Specifically, Overhead = Duration - Science Target Integration Times

Table 3.1: Table of Scan and Sub-Scan Intents

Intent	Comment	GBT	VLA	VLBA
UNSPECIFIED	Sub-Scan; Scan	✓	✓	
ON_SOURCE	Sub-scan	✓	✓	
OFF_SOURCE	Sub-scan	✓	✓	
OBSERVE_TARGET	Scan	✓	✓	
CALIBRATE_AMPLI	Scan		✓	
CALIBRATE_BANDPASS	Scan		✓	
CALIBRATE_FLUX	Scan		✓	
CALIBRATE_FOCUS	Scan	✓		
CALIBRATE_PHASE	Scan		✓	
CALIBRATE_POINTING	Scan		✓	
CALIBRATE_POL_LEAKAGE	Scan		✓	
SYSTEM_CONFIGURATION	Scan		✓	

Table 3.2: Interrelated Terms in *Capability Request Parameters* and *Observation Specification*

	Science		Observation
Spatial	Field Source	$\xrightarrow[\text{Strategy}]{\text{Observing}}$	Source
Spectral	Spectral Spec		Hardware Configuration
Time	Requested Time[a]	$\xrightarrow[\text{Planner}]{\text{Observation}}$	Science Target Integration Time

[a] The Requested Time is determined by the *Observing Strategy*.

The *Capability Request* contains the user request. Through the *Observing Strategy* and the *Observation Planner*, that request is translated into the *Observation Specification*. Table 3.2 presents the mapping of key terms between these two parts of the *Allocation Request*. Figure 3.1 presents the hierarchy of the time related concepts in the *Observation Planner*. To (hopefully) clarify the definitions and concepts above, consider the two simple, but contrived, examples in the Section 3.1 prior to reviewing the in depth details their usage in Chapter 4.

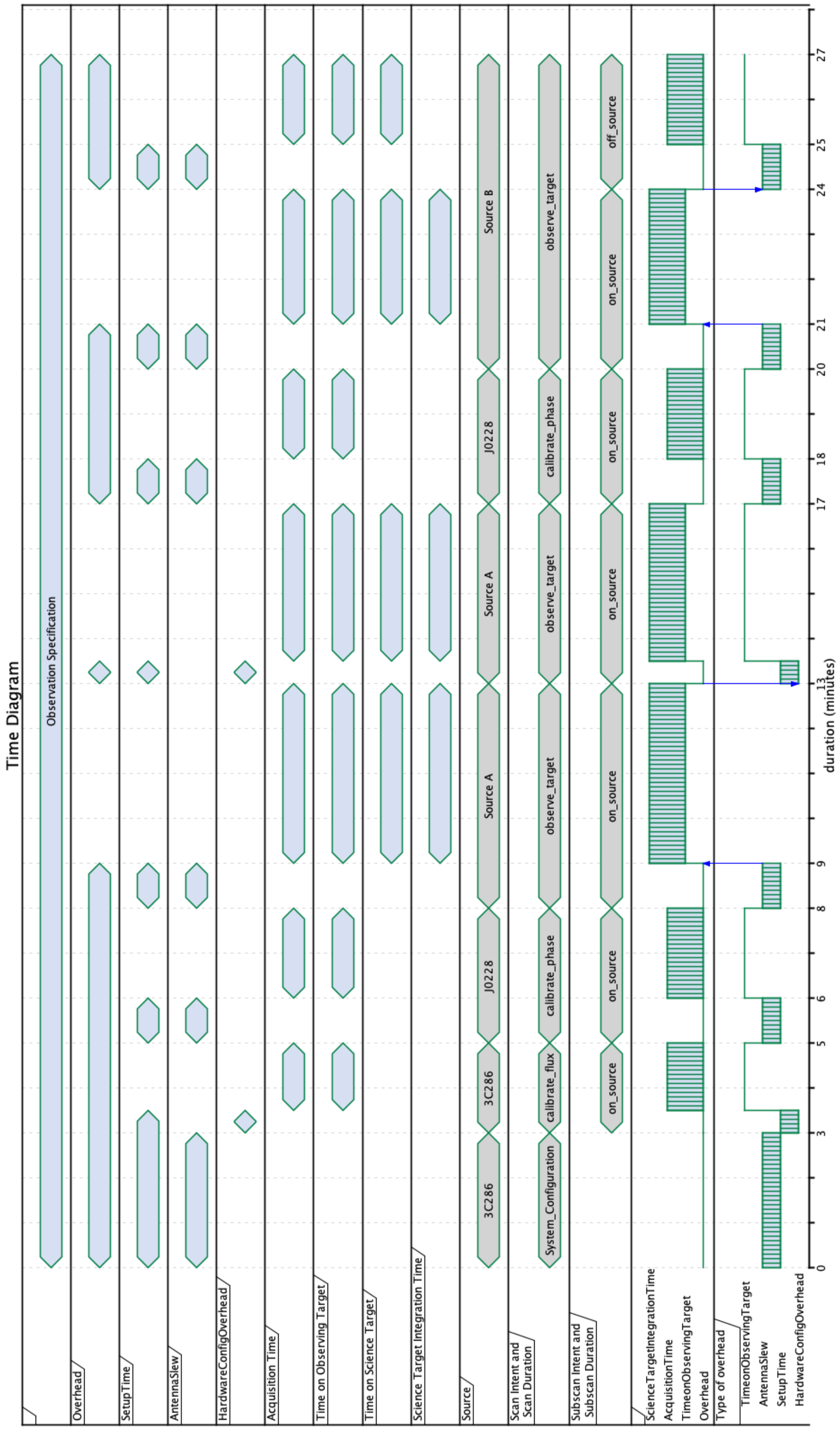


Figure 3.1: Hierarchy and concepts of time in the *Observation Planner*.

3.1 Contrived Examples to Elucidate Concepts and Definitions in the Observation Planner

3.1.1 A Story of VLA Observations of Two Field Sources at One Frequency

Consider a VLA observation of two Science Targets[1], called 'A' and 'B'. The *Observing Strategy* determined the Hardware Configuration is C-band (5 GHz) in D-Configuration and that both Science Targets have a Pointing Pattern of Single Pointing. The *Capability* selects the appropriate *Calibration Strategy*, which will include Complex Gain (Phase Referencing), Flux Density, and Bandpass calibrations. The *Scheduling Strategy* determines the order of the Scan List. Table 3.3 presents an Scan List and summary of the Observation Specification for this example.

- A configuration scan, typically 10 minutes long, is required. It has Scan Intent of SYSTEM_CONFIGURATION.
- The *Calibration Strategy* selects an appropriate Observing Target, called 'Cal-B', that will double as the flux density calibrator and bandpass calibrator.
  - The *Calibration Strategy* determines that the time spent collecting data for Observing Target Cal-B is 280 seconds and a only single sub-scan is needed. Thus, the Acquisition Time is 280 seconds. There Sub-scan Intent is ON_SOURCE, and the Scan Intent is CALIBRATE_FLUX and CALIBRATE_BANDPASS.
  - The duration of a sub-scan can be greater than the Acquisition Time, as it accounts for the Acquisition Time plus any additional time that is not the collecting data. The latter can include the time it takes for the antenna to slew to the position on the sky of the Observing Target (antenna slew time), time for the antenna to settle after its movement (settle time), and the time required for any changes to the hardware configuration (e.g., changing from X-band to C-band). The sum of these is called the Setup Time.
  - The algorithm determines the Setup Time for this sub-scan is 20 seconds.
  - The duration of the Scan is the sum of all the sub-scan times.
- In this example, the RMS Sensitivity determines how much time is needed to address the motivating science of the proposal[2]. The RMS Sensitivity in the *Capability Request* for both FIELD SOURCES is 12 μJy bm^{-1}. The VLA Exposure Time Calculator returns $\sim$ 5 minutes as being sufficient to reach this sensitivity (Figure 3.2). Therefore, the Requested Time is 5 minutes for A and 5 minutes for B.
- The algorithm determines that 22 seconds is the Setup Time for both A and B.
- The *Calibration Strategy* selects an appropriate Observing Target, called 'Cal-A', for the Phase Referencing calibration.
  - The *Calibration Strategy* determines that 80 seconds is the Acquisition Time needed in any sub-scan of the Phase Referencing Observing Target.
  - The Setup Time associated with an observation of the Phase Referencing Observing Target is 20 seconds.
- Observations of the Science Targets will be interleaved with those of the Phase Referencing Observing Target. The Cycle Time for D-configuration at 5 GHz is 10 minutes (Figure 4.2). Given the Scan Duration of the Cal-A, there are 400 seconds (600 seconds - (2 $\times$ 100 seconds)) in

[1]Note, Science Targets are Observing Targets but not all Observing Targets are Science Targets (e.g., calibrators are not Science Targets). The use of these two terms is interchangeable without any loss of meaning for Science Targets. It is a useful distinction, however, for calibrators, particularly when answering questions such as "How much time did the antenna spend collecting data on science sources versus calibrators?"

[2]This is not always true. There are other factors (e.g., Pointing Pattern, uv-coverage) that can contribute to determining the Requested Time.

a Phase Referencing cycle available for scans of the Science Targets because the calibrator must be returned to before the end of the Cycle Time. The Requested Times must be distributed across multiple Sub-scans/Scans because the total Requested Time is already greater than or equal to the Cycle Time.

- Additional constraints, such as a need for uv-coverage, may set a Maximum Acquisition Time for sub-scans.
  * For this example, the Maximum Acquisition Time for Observing Target A is 120 seconds.
  * Observing Target B does not need to share, or have, a Maximum Acquisition Time[3]. For this example, Observing Target B does not have a Maximum Acquisition Time.
- A Maximum Duration, which limits the total time of a Scan (Acquisition Time + Setup Time), can be set. For this example, a Maximum Duration of 300 seconds is set for the Science Targets.
- As a rule, the Acquisition Times for the same Observing Targets (with equivalent Scan Intent and equivalent Sub-scan Intent) should be the nearly equivalent.
- Accounting for the Maximum Acquisition Time, Maximum Duration, and Cycle Time, 3 scans of Observing Target A and 2 scans of Observing Target B are needed to achieve the Requested Time.
- For Sub-scans that share Scan Intent OBSERVE_TARGET, Sub-scan Intent ON_SOURCE, and are the same Science Target, the sum of the Acquisition Time is the Science Target Integration Time for that Science Target. Note, the Science Target Integration Time should only be greater than or equal to the Requested Time.

• A final scan of the Phase Reference Observing Target is added after the last cycle.

F.A.Q.–

Q. What is the total time of Observation Specification (which becomes a VLA Scheduling Block?)

  A. Duration = $\sum$ Setup Time + Time on Observing Targets

Q. How much time is spent observing the Science Targets?

  A. Science Target Integration Times

Q. How much time is spent observing the calibrators?

  A. Time on Observing Targets - Science Target Integration Times

[3]The details of how the Requested Time is distributed amongst the sub-scans for Observing Targets are in § 4.1

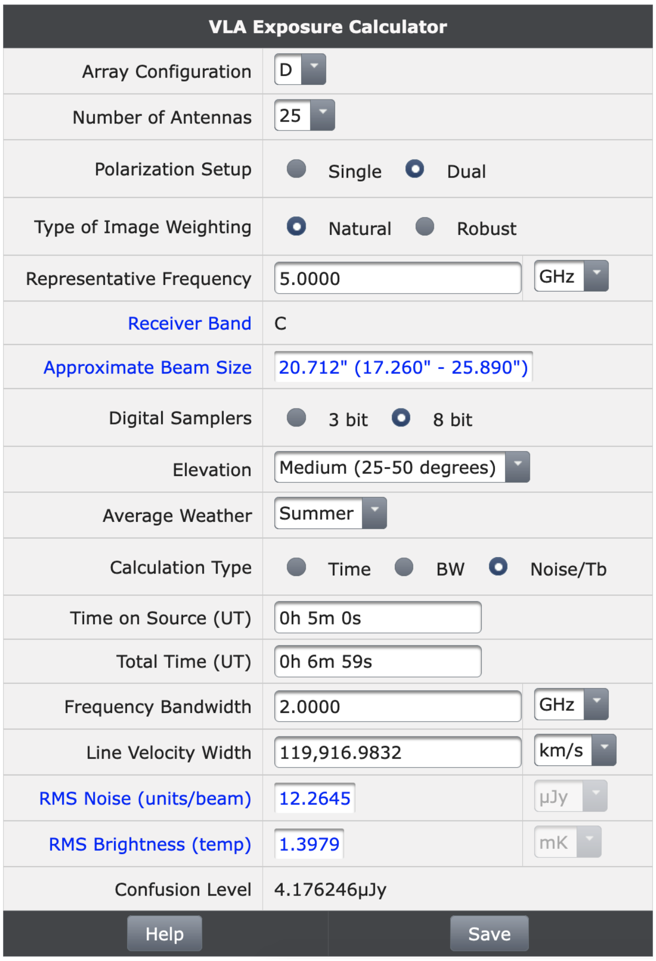


Figure 3.2: Example of Use Case with Time Concepts

Table 3.3: VLA Example Observation Specification

Part 1: Scan List

Scan Intent	Observing Target	Setup Time (s)	Acquisition Time (s)	Sub-scan Intent
SYSTEM_CONFIG	Cal-A	600	0	UNSPECIFIED
CALIBRATE_FLUX	Cal-B	20	280	ON_SOURCE
	Phase Referencing Cycle			
CALIBRATE_PHASE; CALIBRATE_AMPLI	Cal-A	20	80	ON_SOURCE
OBSERVE_TARGET	A	22	110	ON_SOURCE
OBSERVE_TARGET	B	22	150	ON_SOURCE
OBSERVE_TARGET	A	22	110	ON_SOURCE
	Next Cycle			
CALIBRATE_PHASE; CALIBRATE_AMPLI	Cal-A	20	80	ON_SOURCE
OBSERVE_TARGET	B	22	150	ON_SOURCE
OBSERVE_TARGET	A	22	110	ON_SOURCE
	End Cycle			
CALIBRATE_PHASE; CALIBRATE_AMPLI	Cal-A	20	80	ON_SOURCE

Part 2: Summary

Source	Time on Observing Target (s)	Science Target Integration Time (s)
Cal-B	280	0
Cal-A	240	0
A	330	330
B	300	300

Science Target Integration Times = $\sum$ Science Target Integration Time	630 s
Time on Observing Targets = $\sum$ Time on Observing Target	1150 s
Duration = $\sum$ Setup Time + Time on Observing Targets	1940 s
Overhead = Duration - Science Target Integration Times	790 s

3.1.2 A Story of GBT Observations of Two Field Sources at One Frequency

Consider a GBT observations of two Science Targets, called 'A' and 'B'. The *Observing Strategy* determined the Hardware Configuration and that both Science Targets have a Pointing Pattern of Single Pointing. The *Capability* selects the appropriate *Calibration Strategy*, which will include Position Switching and Focus calibrations. The *Scheduling Strategy* determines the order of the Scan List. Table 3.4 shows the Scan List and summary of the Observation Specification for this example.

Table 3.4: GBT Example Observation Specification

Part 1: Scan List

Scan Intent	Observing Target	Setup Time (s)	Acquisition Time (s)	Sub-scan Intent
CALIBRATE_FOCUS	Cal-A	20	180	ON_SOURCE
OBSERVE_TARGET	A	22	110	ON_SOURCE
OBSERVE_TARGET	A	22	110	OFF_SOURCE
OBSERVE_TARGET	B	22	150	ON_SOURCE
OBSERVE_TARGET	B	22	150	OFF_SOURCE

Part 2: Summary

Source	Time on Observing Target (s)	Science Target Integration Time (s)
Cal-A	180	0
A	220	110
B	300	150

Science Target Integration Times = $\sum$ Science Target Integration Time	260 s
Time on Observing Targets = $\sum$ Time on Observing Target	700 s
Duration = $\sum$ Setup Time + Time on Observing Targets	808 s
Overhead = Duration - Science Target Integration Times	548 s

Chapter 4-Calibration Strategy

The Calibration Strategy contains set of prescriptive templates for how to partition and calibrate the *Science Target List*, which is facilitated by the creation of Observing Instructions. The *Capability* makes the selection of what Calibration Strategy to use; for example, the *Capability* would select the Calibration Strategy of GBT Spectral Line Observations for an Observing Type of GBT Spectral Line. The role of the Calibration Strategy in the system is to convert a *Science Target List* into one or more Calibration Plans where a Calibration Plan is expressed as a set of Observing Instructions which can then be scheduled. The following sections detail the Observing Instructions before describing the Calibration Plans. Depending on the reader's familiarity with calibrating and scheduling radio observations however, it may be more helpful to read the Calibration Plans in Section 4.2 before referencing the individual Observing Instructions provided below.

4.1 Observing Instructions

Observing Instructions (OIs) encapsulate information about observations that need to be made, which includes

- how long the observations are required to be observed for,
- information about the ordering of scans and sub-scans,
- how often the observations are required to be observed.

Observing Instructions (OIs) have two primary responsibilities in the system. Given their internal state, a list of scans that have already been scheduled and a list of upcoming scans, the OI determines whether or not scans on it's Observing Target(s) should added to the observation. The second responsibility is given a list of previously scheduled Scans and a Maximum Duration that may be scheduled, the OI returns a list of Scans which advance the state of the Observing Instruction toward completion or satisfy calibration requirements. These manifest as the actions of "Determining if Observation is Required" and "Generating a List of Scans". The TTA System has a set of OIs; the following sections define a non-exhaustive list of the required OIs, which include

- Science Observing Instructions, which are correlated with the *Science Target List*;
- Calibrator Observing Instructions, which contain information about the Observing Target that is required for calibration.

OIs are subject to prerequisites, called Prerequisite Observing Instructions. These are actions that must be done before the OI. A Prerequisite Observing Instruction triggers the inclusion of a particular Calibrator OI or Science OI. The prototypical example for this is the Pointing Calibration Observing Instruction. Table 4.1 briefly summarizes the OIs, and Figure 4.1 provides a illustrative guide for the hierarchy.

4.1.1 Generic Science Observing Instructions

Science Observing Instructions encapsulate the observation of a single row of the *Science Target List*. Science OIs contain the following types of information:

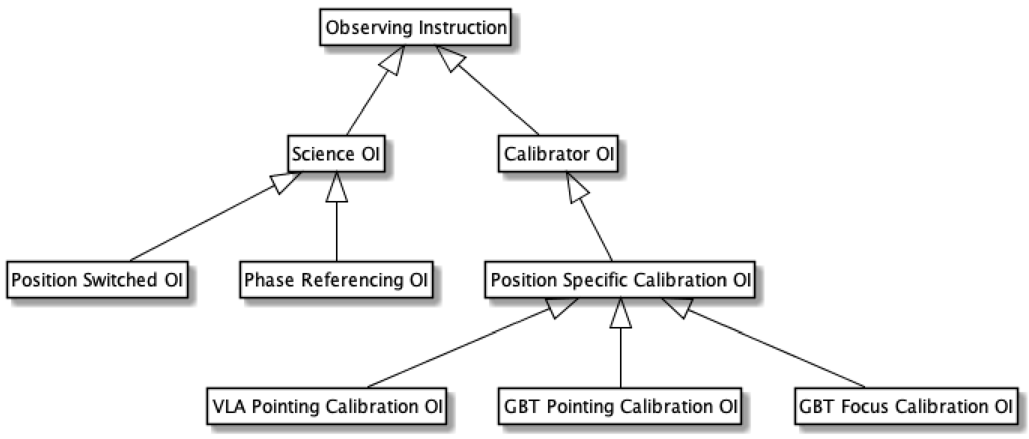


Figure 4.1: Hierarchy of the Observing Instructions.

Table 4.1: Summary of Observing Instructions

Name	Summary	Section
Science OI	Encapsulates the observation of a Science Target	4.1.1
Position Switching OI	A Science OI for moving between on-source and off-source positions the purposes of calibration.	4.1.1.1
Phase Referencing OI	A Science OI for implementing the phase referencing technique for interferometry.	4.1.1.2
Calibrator OI	Encapsulates the observation of a calibrator	4.1.2
Position Specific Cal OI	Instructions for observations pertaining to a distance on the sky over which an OI is valid.	4.1.2.1
VLA Pointing Cal OI	A Position Specific OI for VLA pointing calibrations.	4.1.2.1.1
GBT Pointing Cal OI	A Position Specific OI for GBT pointing calibrations.	4.1.2.1.2
GBT Focus Cal OI	A Position Specific OI for GBT focus calibrations	4.1.2.1.3

- A list of Sub-scan Prototypes to be realized within each Scan. Each Sub-scan Prototype will have an associated weight, which specifies how the Requested Time is distributed (as Acquisition Time) amongst the Sub-scans that share a common Observing Target. The default weight is 1.
- The Requested Time is the total time that data should be acquired on the Science Target. It does not include time spent moving to the Science Target or time spent on calibration.
- The Maximum Scan may not be defined, but in many cases, it is useful to define a maximum length for any single Scan on an Observing Target.
- A list of Prerequisite Observing Instructions (e.g., Calibrator Observing Instructions) that must be checked to see if they need to be observed prior to the Science OI.

There are multiple types of Science OIs (e.g., Position Switching OI, Phase Referencing OI), but they each perform the actions of

❖ Determining if Observation is Required

  – If the Science Target Integration Time in previously scheduled Scans for this OI is greater than or equal to the Requested Time, then this OI does not require observation; otherwise it does.

❖ Generating a List of Scans

- Given the set of Scans that have previously been scheduled and the information about the Scan that is about to be scheduled for this OI, determine if any of the Prerequisite OIs need to be scheduled. If so, the scans they generate should be inserted at the beginning of the returned list of scans.
- Science OIs produce a single OBSERVE_TARGET Scan each time they are called. The Scan should be as long as possible subject to the following constraints.
  * The total time of the scan, excluding Setup Time, should not exceed the Maximum Scan, if it is specified.
  * The duration of the scan, including overheads, should not exceed the Maximum Duration specified when the list of scans is requested.

  The Time on Observing Target, (scan duration - Setup Time) should be distributed among the sub-scans according to their specified weights.

4.1.1.1 Science OI: Position Switching Observing Instruction

A Position Switching Observing Instruction is a specific type of Science OI that takes as input

- the position of the Science Target, called the on-source position;
- an off-source position used for calibration;
- a Hardware Configuration;
- the Requested Time;
- a Cycle Time, which is the maximum time to complete one full cycle of on-source and off-source observations.

The Position Switching Observing Instruction has two Sub-scan Prototypes of equal weight. The first Sub-scan Prototype has the off-source position, a Hardware Configuration, and a Sub-scan Intent of OFF_SOURCE. The second has the on-source position, the Hardware Configuration, and the Sub-scan Intent of ON_SOURCE.

❖ Determining if Observation is Required

- The conditions for determining if an observation is required for a Position Switched Observing Instruction are the same as for a Science Observing Instruction.

❖ Generating a List of Scans

- In general, the list of scans is the same as for the Science OI; however, the scan, including any overhead, must always be less than or equal to the specified Cycle Time.

4.1.1.2 Science OI: Phase Referencing Observing Instruction

A Phase Referencing Observing Instruction implements the phase referencing technique for interferometry. The Phase Referencing Observing Instruction takes as input

- a Calibrator Observing Instruction,
- one or more Science Observing Instructions,
- a Cycle Time, which is the maximum permitted time between subsequent observations of the Calibrator Observing Instruction.

❖ Determining if Observation is Required

  - Observation of a Phase Referencing Observing Instruction is required if any of the Science OIs require observation. Note that a Phase Referencing Observing Instruction may not require observation although its Calibrator Observing Instruction will report that it requires observation.

❖ Generating a list of Scans

  - As with other OI, any Prerequisite Observing Instructions that require observation should be inserted into the returned list of scans prior to the Scans generated by this OI.
  - The list of scans generated by the Phase Referencing Observing Instruction should start with a scan created by the Calibrator Observing Instruction. Note that if this scan is identical to the last scan in the input list of scans, the new scan should be omitted.
  - The objective now is to schedule as much time on the Science Targets before the Cycle Time is reached and another scan from the Calibrator Observing Instruction must be scheduled. The available time shall be scheduled such that
    * The Science OIs are prioritized inversely to their completion fraction. Here, the completion fraction is the ratio of the Science Target Integration Time already in previous scans to the Requested Time of the Science OI.
    * The average time, excluding overhead, for each Science OI is greater than the total overhead for the scan. If this is not the case, remove the lowest priority Science Observing Instructions until it is.
    * The total Acquisition Time of the Scans should be allocated proportionally to each OI's remaining time (Requested Time – previous Acquisition Time).
    * Each Science OI should account all of the time allocated to it even if it requires multiple scans to do so; in this case, all of the scans of a Science Observing Instruction should have equal Acquisition Times.
  - Finally, another scan from the Calibrator Observing Instruction should be included as the final scan in the returned list of scans.

4.1.2 Generic Calibrator Observing Instruction

Calibrator Observing Instructions differ from Science OIs in that Requested Time mostly does not affect their need to be observed. The simplest form is the generic Calibrator Observing Instruction which requires

- a list of one or more Sub-scan Prototypes;
- a list of Scan Intents; note that each Scan has all of these intents;
- the Acquisition Time for each sub-scan;
- the Repeat Time, which is how often this calibration must be repeated (This could be a time or a flag designating that the calibrator should always be observed or should be observed exactly once);
- a list of Prerequisite Observing Instructions (probably Calibrator Observing Instructions) which must be checked to see if they need observed prior to this Calibrator Observing Instruction.

❖ Determining if Observation is Required

  - Whether a Calibrator Observing Instruction needs to be observed is based on the Repeat Time.
    * If the flag designating that it should always be observed is set, then the response should be True.
    * If the flag designating that it should be observed exactly once is set, then the response should be True if and only if the Calibrator has never been observed, otherwise False.

        * If a repeat duration is specified, the response should be True if it has never been observed or if the duration since last observation is greater than or equal to the specified Repeat Time, otherwise False.

❖ Generating a List of Scans

  – As with other Observing Instructions, any Prerequisite OIs that require observation should be added to the beginning of the return list of scans.
  – Calibrators generally produce a single scan (aside from any prerequisites) with the specified set of Scan Intents. Each Sub-scan Prototype in the input list should be scheduled with the specified Acquisition Time. Setup Times should be calculated based on the information in the Sub-scan Prototype.

4.1.2.1 Calibrator OI: Position Specific Calibration Observing Instruction

Some forms of calibration are only valid near the region of the sky where the measurement is made. A Position Specific Calibrator Observing Instruction is a type of Calibrator Observing Instruction that takes as input

- the Maximum Region of Validity, which is the distance on the sky over which this Observing Target does not need to be re-observed.

❖ Determining if Observation is Required

  – The conditions for determining if an observation is required for a Position Specific Calibration Observing Instruction are the same as for a Calibrator OI. If any of those conditions are True, then the response should be True. However even if the response to all of the usual calibrator conditions is False, a Position Specific Calibration Observing Instruction requires observation if any of the next Sub-scan Prototypes have a position that is greater than the Region of Validity from where this calibrator was last observed. Note that it is important to consider the rotation of the Earth while making this calculation.

❖ Generating a List of Scans

  – No additional modification of this behavior is required beyond that for the Calibration Observing Instruction.

4.1.2.1.1 Position Specific Calibration OI: VLA Pointing Calibration Observing Instruction

A VLA Pointing Calibration Observing Instruction is a type of Position Specific Calibration Observing Instruction which requires only the specification of a Source.

❖ Determining if Observation is Required

  – No additional modification of this behavior is required beyond that for the Position Specific Calibration Observing Instruction.

❖ Generating a List of Scans

  – The VLA Pointing Calibration is actually composed of 5 Sub-scans but the on-line system provides a single scan shortcut that represents it as a single scan.
  – The returned list of scans contains a single scan with a Scan Intent consisting only of CALIBRATE_POINTING. The scan should contain a single Sub-scan with an Acquisition Time of 150 seconds, the specified FIELD SOURCE, and the specific Hardware Configuration of "X-Band Pointing."
  – Overhead should be calculated as usual when moving to the Source.

4.1.2.1.2 Position Specific Calibration OI: GBT Pointing Calibration Observing Instruction

4.1.2.1.3 Position Specific Calibration OI: GBT Focus Calibration Observing Instruction

4.2 The Strategies

A Calibration Strategy will

- partition the *Science Target List* in two ways:
  - An Initial Partition, which is a *Facility* dependent ....
  - A final Partition, ...
- create the required Observing Instructions based on the *Science Target List*, which is the Calibration Plan.

4.2.1 GBT Spectral Line Observation

Some text briefly giving an overview best practices for GBT spectral line observing...

- Final Partitioning
  - If the *Science Target List* contains a single Source but has two or more Hardware Configurations and the Requested Time associated with each Hardware Configuration is less than one hour, these Science Targets should be grouped in subsequent steps.
  - Otherwise, the *Science Target List* should be partitioned based on the Clustering Algorithm described in Section 6.2.
  - Note: At some point we need to include observability here and breaking down the list where we need to repeat for integration time. Ignore for now.
- Observing Instruction Creation
  - Each of the partitioned sets of Science Targets should be treated independently going forward.
  - If each of the Science Targets in the set has a Pointing Pattern equal to Single Pointing, create a Position Switching Observing Instruction (§ 4.1.1.1) with the Science Target and Hardware Configuration. This OI takes the Requested Time as input. The position of the off-source region should be offset from the Science Target by XX, representing an upper limit on set up time due to telescope motion.

    We could just hard code an upper overhead into the Position Switching Observing Instruction; alternatively, we could specify the real off-source position.
  - The Cycle Time of the Position Switched Observing Instruction is determined by the receiver (FRONT-END) in use according to Table 4.2.
  - For each unique Hardware Configuration, create a Calibrator Observing Instruction (§ 4.1.2) with the single Scan Intent of CALIBRATE_FLUX and a single Sub-scan Intent of ON_SOURCE. The Hardware Configuration should be the same as for the Science Target.
  - Create a GBT Pointing Calibrator OI (§ 4.1.2.1.2) and a GBT Focus Calibrator OI (§ 4.1.2.1.3) for each unique Hardware Configuration and set them as prerequisites for the Calibrator and Position Switched Observing Instructions that share the Hardware Configuration.

Table 4.2: Placeholder Table of Cycle Times

Band	Receiver	Maximum Cycle Time

4.2.2 VLA Interferometric Calibration

Some text briefly giving an overview of the best guiding practices for VLA calibrations...

- ❖ Final Partitioning
  - If the *Science Target List* contains a single Source but has two or more Hardware Configurations and the Requested Time for each Hardware Configuration is less than one hour, these Science Targets should be grouped in subsequent steps.
  - Otherwise, the *Science Target List* should be partitioned based on the Clustering Algorithm described in Section 6.2.
  - Use the Clustering Algorithm (§ 6.2) to determine groups of Science Observing Instructions that can share a phase calibrator. (For now, assume all Science Targets with the same Hardware Configuration can share a phase calibrator).
  - Note: At some point we need to include observability here and breaking down the list where we need to repeat for integration time. Ignore for now.
- ❖ Observing Instruction Creation
  - For each Science Target in the *Science Target List* create a Science Target Observing Instruction (§ 4.1.1) with the Source, Hardware Configuration, and Requested Time from the partitioned set.
  - Create a Phase Referencing Observing Instruction (§ 4.1.1.2) for each cluster of Science Observing Instructions. The Cycle Time should be set according to Table 4.2.
  - For each Phase Referencing Observing Instruction, select an appropriate calibrator (§ 5.1.3) and create a Calibrator Observing Instruction (§ 4.1.2) that has Scan Intents of CALIBRATE_AMPLI and CALIBRATE_PHASE and is flagged as always requiring observation. The Acquisition Time should be the maximum of
    - ∗ a time based on required signal to noise ratio and the flux of the source;
    - ∗ 180 seconds.

    For now should it should be set to 180 seconds.
  - Select Observing Targets appropriate for the intents of CALIBRATE_FLUX and CALIBRATE_BANDPASS for each unique Hardware Configuration (§ 5.1.3). Create Calibrator Observing Instructions with the execute "once flag" set for each of the selected calibrators. The Acquisition Time is 180 seconds.
  - If the CALIBRATION PARAMETER of "Polarization Study" is set, select an appropriate Observing Target for the intents of POLARIZATION_LEAKAGE and create a Calibrator Observing Instruction with an Acquisition Time of XX seconds (§ 5.1.3).
  - If any of the Hardware Configurations have frequencies of 15 GHz or above, create a VLA Pointing Observing Instruction. Set this as a prerequisite for all Observing Instruction that have Hardware Configurations above 15 GHz.

Table 3.1: Cycle times in minutes by configuration and frequency band				
Band (Frequency Range)	Array Configuration and Cycle Time in Minutes			
	A	B	C	D
4 (54-86 MHz)	30	30	30	30
P (224-480 MHz)	30	30	30	30
L (1-2 GHz)	15	15	15	15
S (2-4 GHz)	15	15	15	15
C (4-8 GHz)	8	10	10	10
X (8-12 GHz)	8	10	10	10
Ku (12-18 GHz)	6	7	8	8
K (18-26.5 GHz)	4	5	6	6
Ka (26.5-40 GHz)	3	4	5	6
Q (40-50 GHz)	2	3	4	5

Figure 4.2: Cycle Times in Minutes by Configuration and Band

Chapter 5-Misc

5.1 Referenced Specification Constraints and Related Calculations

5.1.1 Setup Time

The Setup Time is time spent not collecting data. This includes the time it takes for an antenna to slew between one source to another (ordered), the time it takes for the antenna to settle to a nominal state to resume collecting data (settle time), and the time it takes for any changes in the hardware configuration between the previous observing state and the next observing state to take affect (hardware configuration overhead).

- Antenna Slew Calculation (VLA, GBT...)
- Table of settle times
- Table of hardware configuration overheads

5.1.2 Sensitivity Calculators

5.1.2.1 VLA Sensitivity Calculator

5.1.3 Catchall: Needs to be written

- How to select an appropriate Phase Calibrator (Calibration Strategy)
- Select Calibrators in General

5.1.3.1 Antenna Motion

Toy code exists but needs written up.

Chapter 6-Partitioning

Overview – The *Calibration Strategy* applies two partitioning algorithms, Initial Partitioning and Final Partitioning, to the *Science Target List* to form clusters of Science Targets that can then be scheduled.

6.1 Initial Partitioning

The *Capability* selects the Strategy for the initial partitioning of the *Science Target List*, and Partition Instructions provide the information needed to do so. The types of Partition Instructions are

- VLA Configuration Partition Instructions (if applicable; Section 6.1.2),
- Hardware Configuration Partition Instructions (Section 6.1.3),
- Distance Partition Instructions (Section 6.1.4),
- Setup Time Partition Instructions (Section 6.1.5).

Partition Instructions utilize Scipy's Hierarchy[1], Linkage[2], and fcluster[3] to perform hierarchical clustering. A Partition Instruction will

❖ Construct a linkage matrix using scipy.cluster.hierarchy.linkage, which takes as inputs

  – a set of Science Targets,
  – a custom metric that defines a distance function,
  – a method that specifies the linkage algorithm to use in calculating the distance.

The use of distance here is not necessarily the angular distance between astronomical objects; it is the dissimilarity between two objects for a given metric. The linkage algorithm methods defined in the documentation for the linkage are single, complete, average, weighted, centroid, and ward.

❖ Form flat clusters based on the linkage matrix using scipy.cluster.hierarchy.fcluster, which takes as inputs

  – a linkage matrix,
  – a criterion for forming flat clusters,
  – a threshold for forming clusters.

From the criterion defined in the documentation for fcluster, the Partition Instructions use the criterion of "distance", which "forms flat clusters so that the original observations in each flat cluster have no greater a cophenetic distance than [the threshold]"[3].

The clusters formed by fcluster consist of a hierarchical list of nodes. The nodes are the input Science Targets and the clusters to which the Science Targets belong. Commonly, a Dendrogram tree is shown to

[1]`https://docs.scipy.org/doc/scipy/reference/cluster.hierarchy.html`
[2]`https://docs.scipy.org/doc/scipy/reference/generated/scipy.cluster.hierarchy.linkage.html`
[3]`https://docs.scipy.org/doc/scipy/reference/generated/scipy.cluster.hierarchy.fcluster.html#scipy.cluster.hierarchy.fcluster`

visualize the relationship between the nodes. In Figure 6.1, the tree shows the hierarchical relationship between Nodes for a list of Science Targets based on the angular separation between the Sources. The distance between nodes is determined by the choice of the distance function and the linkage algorithm in scipy.cluster.hierarchy.linkage. The solid, horizontal black line represents a cut across the tree; the partitioning occurs where the cut intersects with the branches of tree. The height at which the cut is made is determined by the value of the threshold for forming clusters in scipy.cluster.hierarchy.fcluster.

The Strategy calls the Partition Instructions to partition the *Science Target List*. Depending on the Strategy, iterations through Partition Instructions can further fragment clusters; this produces a set of lists of nodes. Section 6.1.1 presents an example of this fragmentation. Figure 6.2 provides an overview of the Initial Partitioning algorithm from which a set of lists of nodes is built before being passed to the Final Partitioning (Section 6.2).

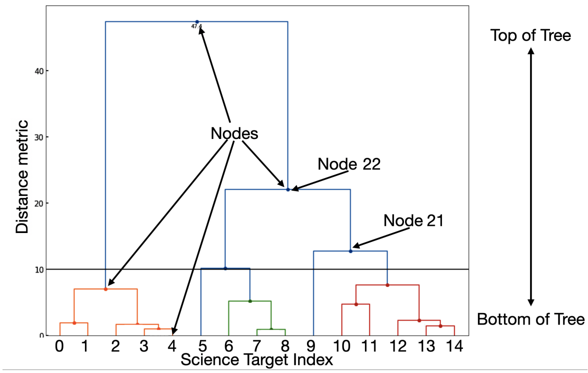


Figure 6.1: Example Dendrogram tree for 15 Science Targets using angular distance on the sky as the custom metric. The solid black line at y = 10 cuts the tree, yielding 5 clusters.

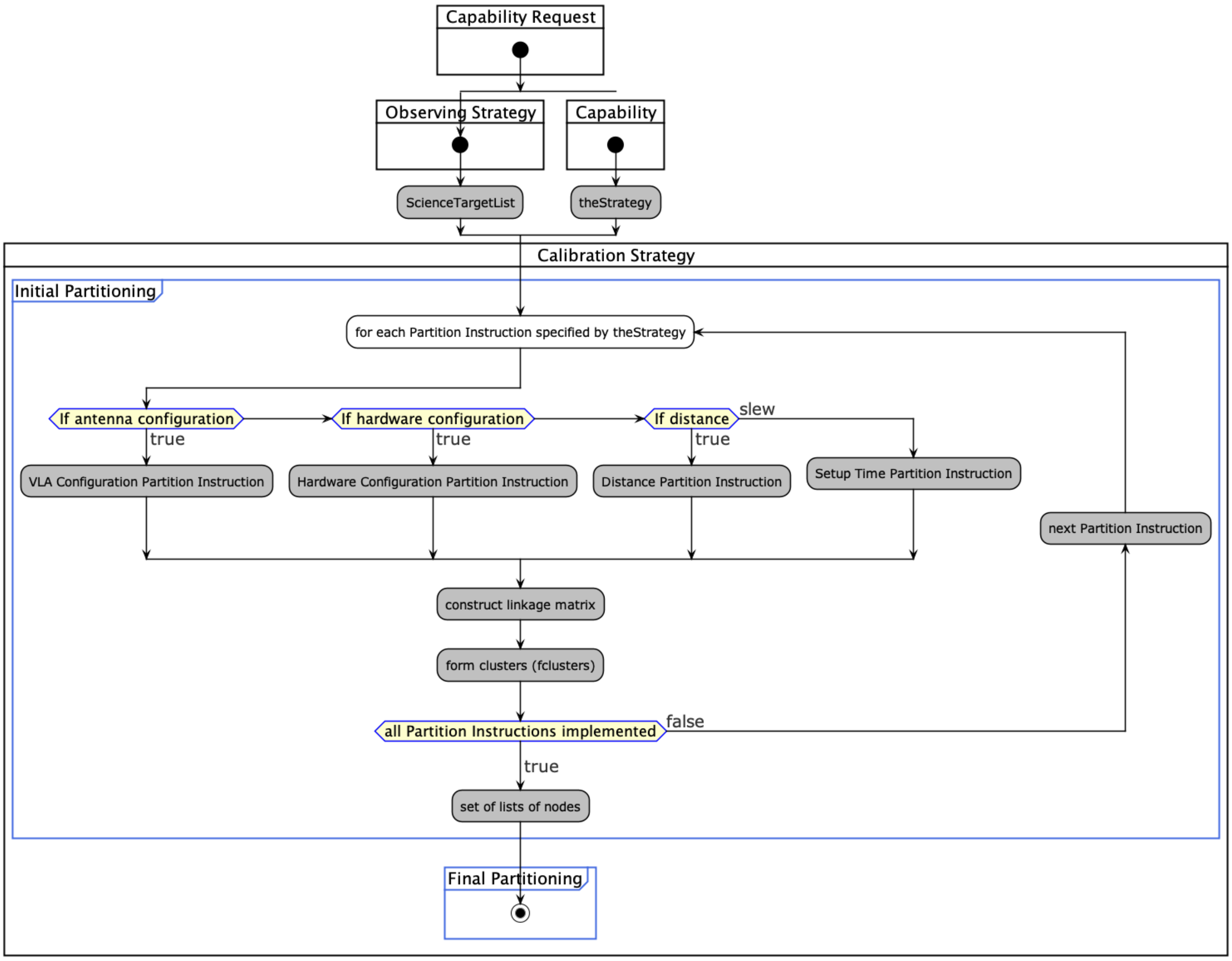


Figure 6.2: Simple diagram for Initial Partitioning.

6.1.1 Examples of Initial Partitioning

Consider Figure 6.3 and the following examples of two Sources, A and B, and two Hardware Configurations, Hardware 1 and Hardware 2.

- If the *Science Target List* contains two Sources but each has two (or more) Hardware Configurations with less than an hour of Requested Time per Hardware Configuration, the Strategy selected by the *Capability* is a Distance Partition Instruction.

Ex 1. If the two Sources are not partitioned in distance, the result is one cluster with all Sources and all Hardware Configurations (i.e., all Science Targets).

Ex 2. If the Sources are partitioned by the Distance Partition Instruction, there are 2 clusters: one for each Source, where each Source has both Hardware Configurations.

- If the *Science Target List* contains two Sources, has two (or more) Hardware Configurations per Source, and more than an hour of Requested Time per Hardware Configuration, the Strategy includes a Hardware Configuration Partition Instruction and a Distance Partition Instruction.

Ex 3. If the two Sources are not partitioned in distance but the Hardware Configuration is partitioned into two clusters, the result of Initial Partitioning is two clusters: each one containing the Sources but different Hardware Configurations.

Ex 4. If the Sources are partitioned by the Distance and Hardware Configuration Partition Instructions, then there are four clusters: one for each Science Target.

Ex 5. If the Sources are partitioned by the Distance Partition Instruction but not the Hardware Configuration Partition Instruction, there are two clusters: each one containing the Sources but different Hardware Configurations.

Ex 6. If the Sources are not partitioned by the Distance or Hardware Configuration Partition Instructions, there is 1 cluster composed of all the Science Targets.

6.1.2 Configuration Partition Instructions

One VLA Configuration is permitted per *Observation Specification*; *Capability Requests* comprised of multiple VLA Configurations are partitioned into different clusters.

❖ linkage

  - The custom metric compares the VLA Configuration of any two Science Targets.
    * If equal, the metric returns 0.
    * If different, the metric returns 1.
  - Linkage algorithm method is "complete".

❖ fcluster

  - The threshold is set to 0.5.

6.1.3 Hardware Configuration Partition Instructions

The Hardware Configuration Partition Instructions is a frequency based partitioning of the *Science Target List* following prescriptive templates. The template is specified in the Strategy selected by the *Capability*.

❖ linkage

  - The custom metric compares the frequency bands of any two Science Targets. The metric returns the dissimilarity value specified in the template.
  - Linkage algorithm method is "complete".

❖ fcluster

  - The threshold is set to 15.

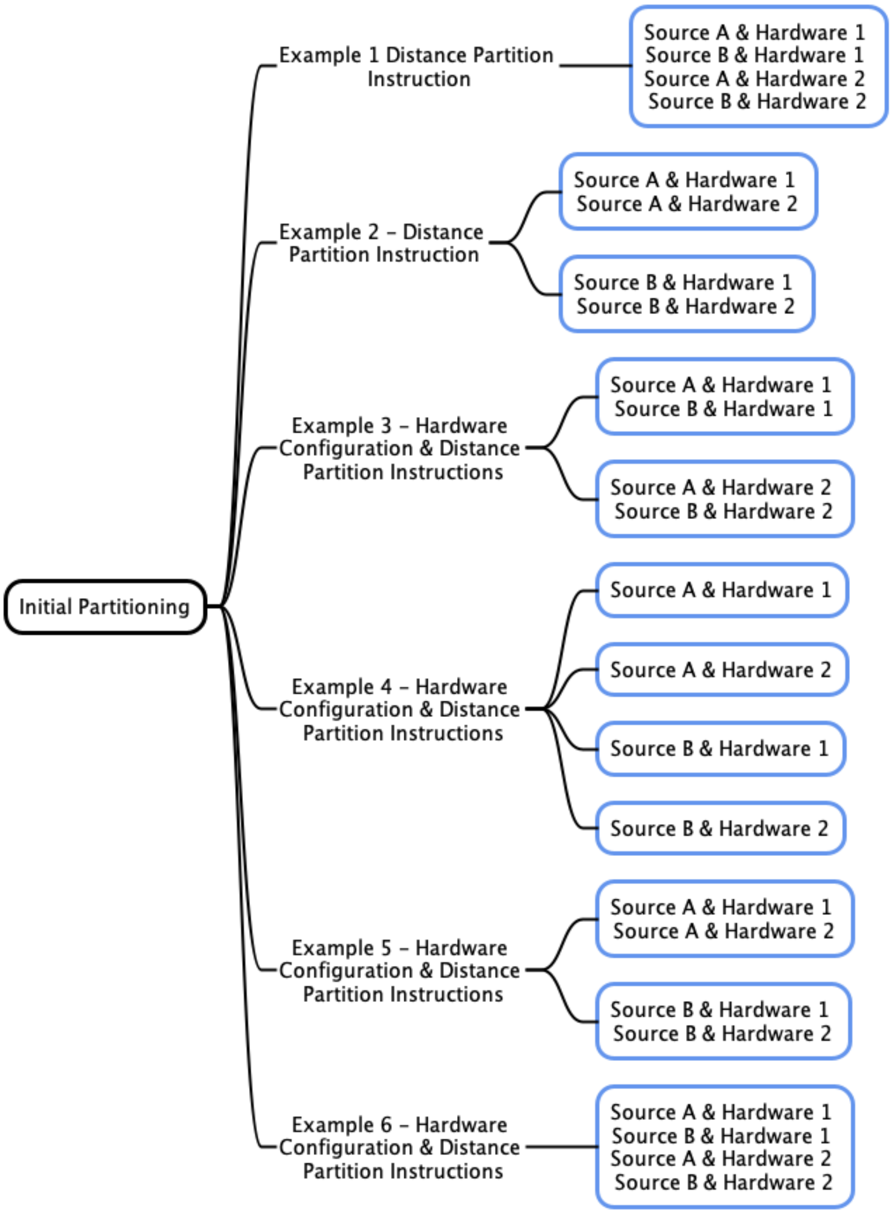


Figure 6.3: Example Initial Partitioning for two Sources and two Hardware Configurations.

6.1.3.1 Hardware Configuration Templates

6.1.3.1.1 VLA

6.1.3.1.2 GBT

6.1.4 Distance Partition Instructions

The Distance Partition Instructions partitions the *Science Target List* based on the angular separation between Sources.

- ❖ linkage
  - The custom metric uses the Vincenty Formula[4] to calculate the angular separation between any two Sources.
  - Linkage algorithm method is “complete”.

[4] https://en.wikipedia.org/wiki/Great-circle_distance

- fcluster
  - The threshold is set by the Strategy. The default value is 10 (degrees).

6.1.5 Setup Time Partition Instructions

The Setup Time Partition Instructions account for the Antenna slew time and the Hardware Configuration overhead (see Chapter 3 for definitions).

- linkage
  - The custom metric returns a time in seconds that is the sum of the (1) simulated motion of antennas (Section 5.1.3.1)and (2) the Hardware Configuration overhead for a list of Science Targets.
  - Linkage algorithm method is "complete".
- fcluster
  - The threshold is set by the Strategy. The default value is 540 (seconds).

6.2 Final Partitioning

The Final Partitioning takes a set of lists of nodes as input and has two primary clustering instructions: Time Clustering Instructions and Local Sidereal Time (LST) Clustering Instructions. The Time Clustering Instructions can partition a list of nodes by the total Requested Time and/or by the overhead incurred by a list of Science Targets. The Strategy specifies the parameters of the partition. The LST Clustering Instructions evaluate a set of clusters for LST considerations and create a final set of clusters that are assigned to one or more *Observation Specifications* which can then be scheduled.

6.2.1 Time Clustering Instructions

Hierarchical Definitions and Concepts –

1. A cluster is a group of Science Targets.
2. The “maximum total Requested Time” specifies the limit on the sum of the Requested Time for all Science Targets in a cluster.
3. The Filling Time specifies a minimum total Requested Time in a cluster with respect to the maximum total Requested Time.
4. The “maximum Overhead” specifies a limit to the overhead of a cluster e.g., the total Setup Time associated with the Science Targets assigned to a cluster.
5. The “maximum Extent on Sky” specifies the maximum angular distance between any pair of Science Targets in a cluster.
6. A “good cluster” is the state describing a cluster when the following conditions are true
   - (1) None of the Science Targets have been assigned to a another cluster.
   - (2) The total Requested Time is less than the maximum total Requested Time.
   - (3) The total Requested Time divided by the maximum total Requested Time is greater than or equal to the Filling Time.
   - (4) The overhead is less than the maximum Overhead.
   - (5) The angular size of the cluster is less than the maximum Extent on Sky.

The Time Clustering Instructions attempts to build “good clusters” from the list of nodes by considering each node first, recalling that nodes can be a list of Science Targets or a single Science Target. The algorithm tracks if the Science Targets have been assigned to a cluster and will continue to evaluate nodes or build clusters until all Science Targets have been assigned to a cluster.

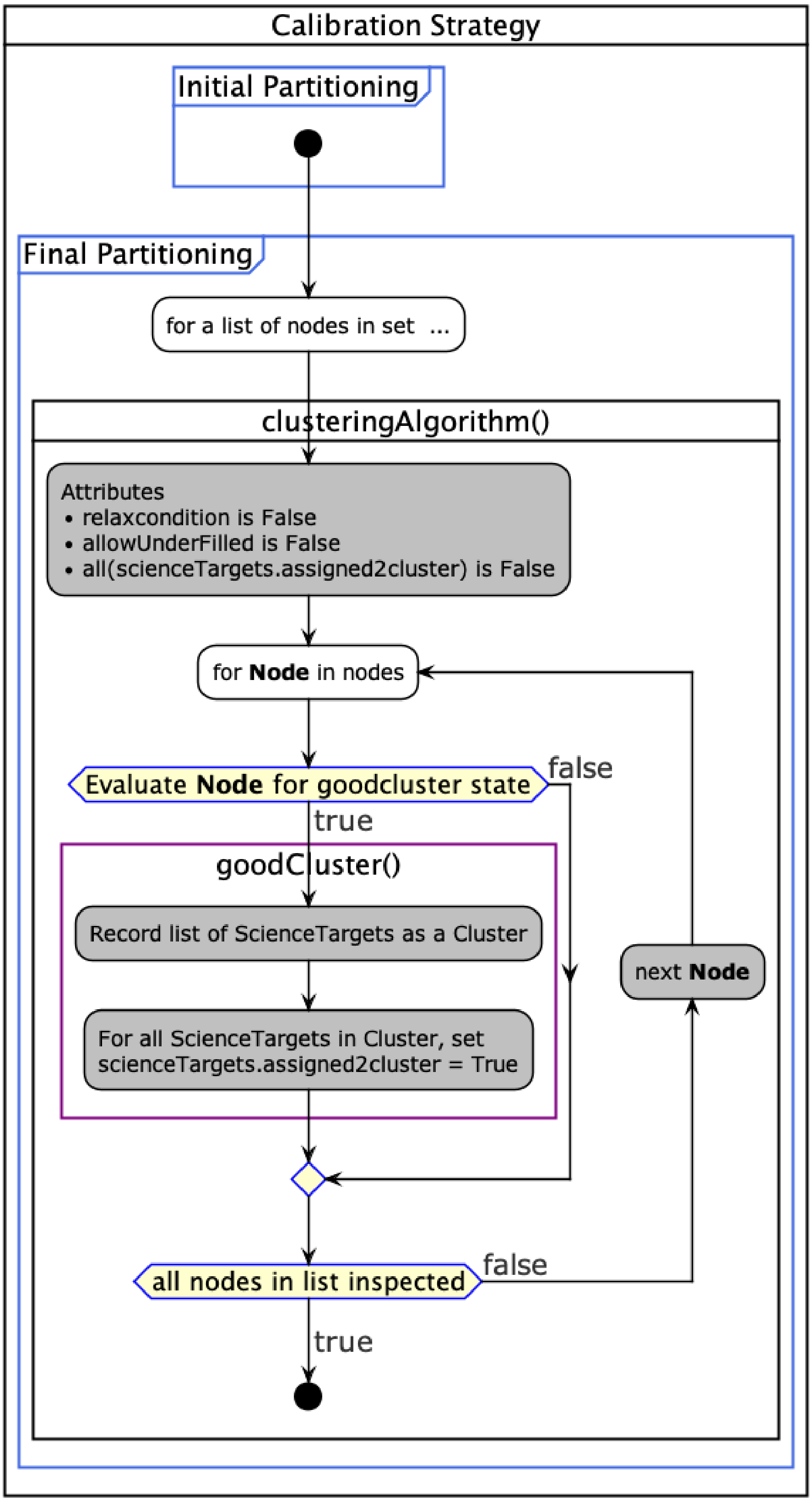


Figure 6.4: Simple flow diagram for the Final Partitioning. See text for definition of ”goodCluster” in Section 6.2, Hierarchical Definitions and Concepts, Item 6.

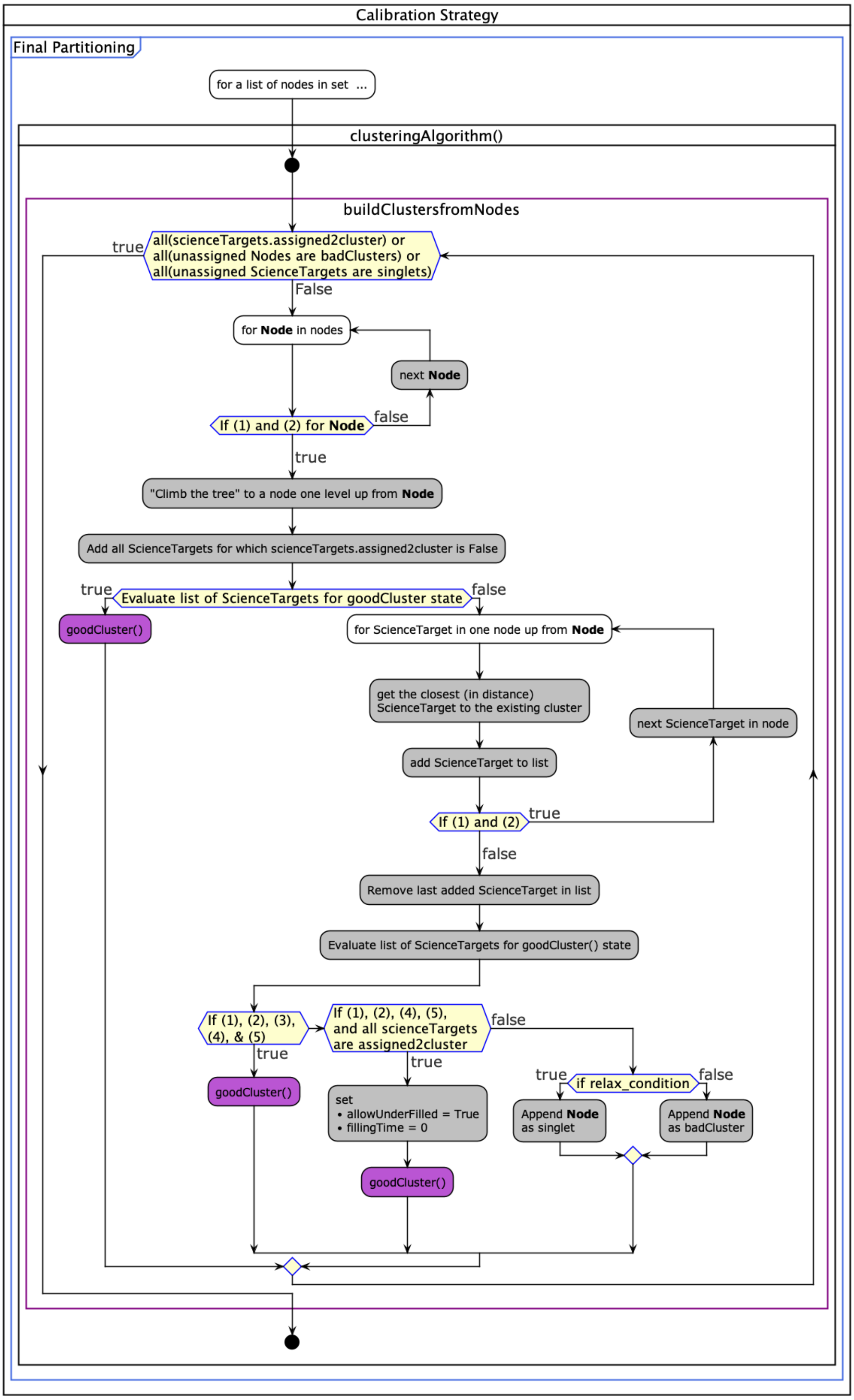


Figure 6.5: Continuation of Figure 6.4. See text for definitions of conditions (1), (2), etc. in Section 6.2, Hierarchical Definitions and Concepts, Item 6.

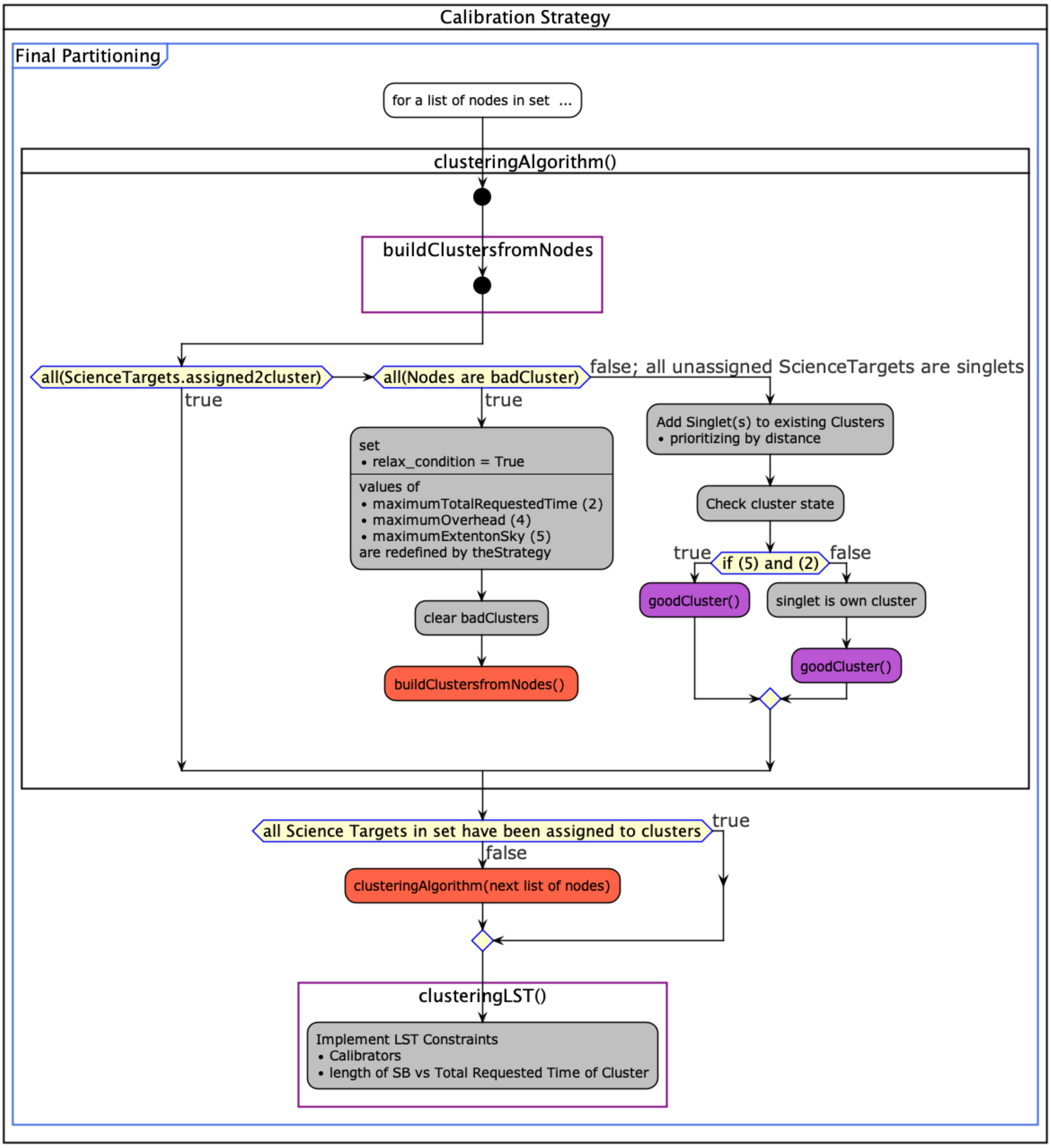


Figure 6.6: Continuation of Figure 6.5. See text for definitions of conditions (1), (2), etc. in Section 6.2, Hierarchical Definitions and Concepts, Item 6.

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