Recommended Minimum Switching Periods for VEGAS

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1 INTRODUCTION

VEGAS can be configured to provide minimum switching periods that are extremely short – so short, in fact, that the limiting factor on the switching period can be the blanking time introduced by the GBT system. The purpose of this memo is to document the different blanking times in the GBT system and recommend minimum switching periods to avoid significant data loss.

During observations, blanking is triggered by the following processes:

- noise diode state changes (i.e., on to off or off to on),
- frequency switch state changes (i.e., signal to reference or reference to signal), and
- Doppler tracking.

Blanking can be introduced either by VEGAS itself (the noise diode case) or by the LO (frequency switching and Doppler tracking cases). The hardware exposure times, minimum state times, and minimum blanking times per state for VEGAS are given in Table 1. The blanking introduced by the LO is discussed below. The blanking done by the system occurs concurrently, so that the total blanking seen by the system is just the maximum blanking time, not the sum of the available blanking times; see Figure 2 for an example.

The noise diode requires the least amount of blanking. Pulsar observations suggest that the noise diode transitions between states in less than 20 microseconds (P. Demorest, private communication), which is much smaller than the minimum blanking time for VEGAS (see Table 1). Therefore, any noise diode transitions are assumed to occur within the minimum VEGAS blanking time for each mode.

The blanking due to the LO has been measured for the new LO1 (upgraded June 2014). The Doppler update, which can occur as often as every switching period, incurs 35ms of blanking for the PF, L, S and C-band receivers and 58ms of blanking for X through W-band. In both cases, the blanking due to state changes for frequency switching is 11ms. In this memo, we use the current configuration tool values for the blanking: 38ms for the Doppler update and 16ms for the frequency switch state change. For frequency switched observations, the Doppler update always occurs at the beginning of a switching cycle. For total power observations, the switching occurs once every n switching periods for switching periods greater than 0.5s and at multiples of 0.5s for switching periods less than 0.5s.

The effects of blanking in total power and frequency switching observing modes without Doppler tracking are straight-forward to determine. In Section 2, we parameterize the system blanking in

Table 1: VEGAS Hardware Parameters

Mode (1)	Spectral Resolution (kHz) (2)	Hardware Exposure (s) (3)	Minimum Blank Time per State (s) (4)	Minimum State Time (s) (5)
1	1464.8438	0.0005	0.0005	0.0010
2	91.5527	0.0014	0.0014	0.0028
3	65.9180	0.0020	0.0020	0.0040
4	5.7221	0.0100	0.0014	0.0114
5	2.8610	0.0199	0.0028	0.0227
6	1.4305	0.0301	0.0056	0.0357
7	3.0518	0.0102	0.0026	0.0128
8	1.5259	0.0203	0.0052	0.0256
9	0.7629	0.0301	0.0105	0.0406
10	0.7153	0.0056	0.0112	0.0168
11	0.3576	0.0112	0.0224	0.0336
12	0.1788	0.0280	0.0447	0.0727
13	0.0894	0.0447	0.0895	0.1342
14	0.0447	0.0671	0.1790	0.2461
15	0.3576	0.0056	0.0224	0.0280
16	0.1788	0.0112	0.0447	0.0559
17	0.0894	0.0336	0.0895	0.1230
18	0.0447	0.0447	0.1790	0.2237
19	0.0224	0.0895	0.3579	0.4474
20	5.7221	0.0051	0.0014	0.0065
21	2.8610	0.0101	0.0028	0.0129
22	1.4305	0.0301	0.0056	0.0357
23	0.7153	0.0405	0.0112	0.0517
24	0.3576	0.0755	0.0224	0.0979
25	4.1199	0.0070	0.0019	0.0090
26	2.0599	0.0141	0.0039	0.0180
27	1.0300	0.0398	0.0078	0.0476
28	0.5150	0.0544	0.0155	0.0699
29	0.2575	0.1010	0.0311	0.1320

Col (1): VEGAS mode
Col (2): Spectral resolution of mode.
Col (3): Hardware exposure time. This time is the fastest that VEGAS can produce data. Producing data this quickly is only possible when not doing any switching.
Col (4): Blanking time per switching state. Note that in some cases the blanking time is a significant fraction of the minimum state time.
Col (5): Minimum time per switching state including the minimum blanking time.

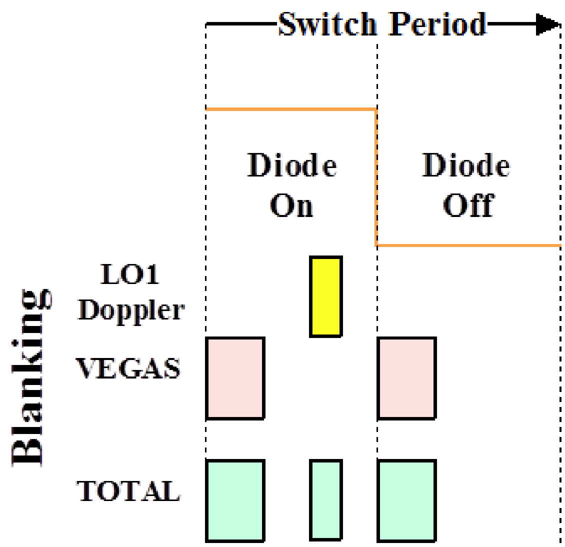

Figure 1: Blanking during total power observations with the noise diode (`tp`). The orange line shows the noise diode turning on and off. The red boxes show the blanking introduced by VEGAS, which is triggered by state changes. The yellow box is the blanking introduced by the LO for Doppler tracking, which can occur as often as once per switching cycle for switching cycles greater than 0.5s. For switching cycles less than 0.5s, the update can occur at least every 0.5s. The total blanking introduced on a state change is just the maximum of all the blanking values, not the sum. However, the blanking due to Doppler tracking will add to the blanking from the noise diode state change in the worse case scenario (shown here).

these cases as a function of the switching period. Quantifying the blanking due to Doppler tracking is more difficult. In Section 3, we provide estimates of the worst possible cases for blanking due to Doppler tracking for mapping and pointed observations.

2 TOTAL POWER AND FREQUENCY SWITCHING OBSERVATIONS WITHOUT DOPPLER TRACKING

For total power observations without the noise diode (i.e., `swtype='tp_nocal'`), the switching period for VEGAS is the hardware exposure value given in Table 1. Note that in this case *only* the switching period is required to be equal to the integration time. Adding the noise diode (i.e., `swtype='tp'`) introduces blanking. The blanking time per switching period for total power observations with the noise diode is

$$t_{blank,tp} = 2.0 * t_{blank,min} \tag{1}$$

The factor of two accounts for the two switching states (calon/caloff).

Similarly for the frequency switching case, the blanking time per switching period is

$$t_{blank,spnocal} = 2.0 * max(t_{blank,LO1}, t_{blank,min}) \tag{2}$$

with the noise diode turned off (`swtype='sp_nocal'`) and

$$t_{blank,sp} = max(2.0 * (t_{blank,LO1} + t_{blank,min}), 4.0 * t_{blank,min}) \tag{3}$$

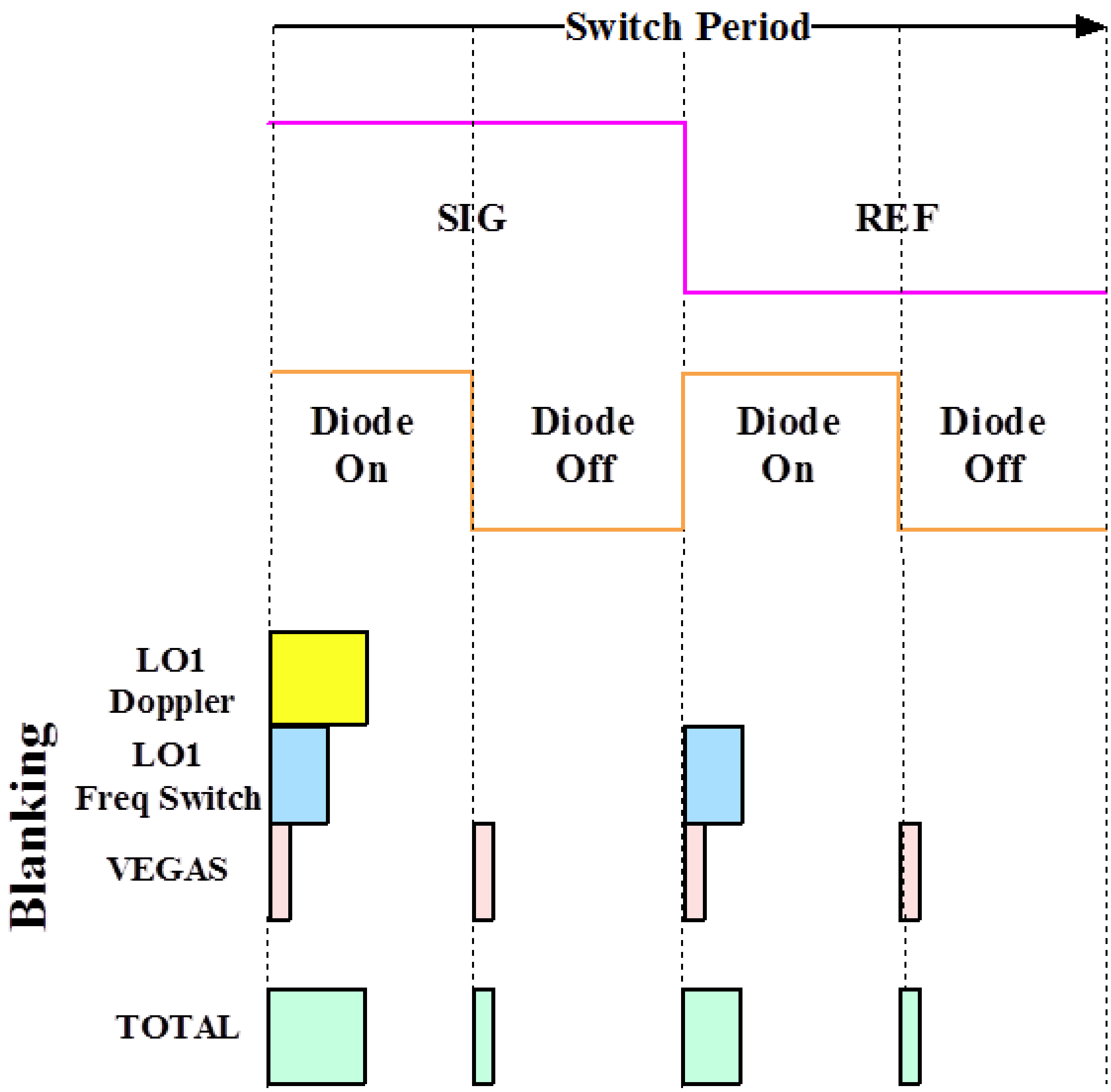

Figure 2: Blanking during frequency switched observations with the noise diode (`sp`). The relative length of the LO blanking and minimum VEGAS blanking time vary depending on the VEGAS mode. For this example, we are assuming that the blanking interval from the LO due to the frequency switch is greater than the minimum blanking time for VEGAS. The magenta line shows the transition from the signal (sig) state to the reference (ref) state for the frequency switch and the orange line shows the noise diode turning on and off. The red boxes show the blanking introduced by VEGAS, which is triggered by state changes. The blue boxes are the blanking introduced by the LO due to frequency switching. The yellow box shows the blanking introduced by the LO while Doppler tracking. For frequency-switched observations, the Doppler tracking update always occurs in the first state of a switching period. The total blanking introduced on a state change is just the maximum of all the blanking values, not the sum.

with the noise diode on (`swtype='sp'`). In the latter case, the first value is the case where the LO blanking value is longer than the VEGAS minimum blank time. The second value is the case were the VEGAS minimum blanking time is longer than the LO blanking value. In addition to these values, the minimum switching period for frequency switching should be greater than 0.25s due to limitations in the LO hardware.

The fraction of blanked data is then

$$f_{blank,tp} = t_{blank,tp}/t_{swper} \tag{4}$$

for the total power case with noise diode case,

$$f_{blank,spnocal} = t_{blank,spnocal}/t_{swper} \tag{5}$$

for the frequency switching case with the noise diode off, and

$$f_{blank,sp} = t_{blank,sp}/t_{swper} \tag{6}$$

for the frequency switching case with the noise diode.

In Table 2, we list the minimum recommended switching period for each VEGAS mode for observations taken in total power and frequency switching modes with no Doppler tracking. The minimum switching period listed is the greater of either the minimum switching period required for less than 10% blanking or the minimum switching period for VEGAS in that mode.

In some cases, it is possible to choose switching periods shorter than the values given in Table 2, but users are restricted to choosing switching periods greater than the minimum switching periods allowed for each VEGAS mode. For total power observations with the noise diode, the absolute minimum switching period for VEGAS is twice that of the minimum VEGAS switching state in Table 1. For frequency switching with the noise diode, it is four times that of the minimum VEGAS switching state.

For mapping, the recommended integration times should include at least four switching cycles to avoid artifacts in the scanning direction of the map; i.e., tint $\geq$ 4 * swper. You can reduce the integration time to less than four switching cycles if you sample at greater than twice Nyquist in the scanning direction. In effect, the latter option is trading the oversampling between the number of switching periods per integration and sampling in the scanning direction.

3 TOTAL POWER AND FREQUENCY SWITCHED OBSERVATIONS WITH DOPPLER TRACKING

When Doppler tracking, blanking by the LO could result in tens of milliseconds of blanking per switching cycle. How frequently the Doppler corrections are updated depends on the reference frame used, the velocity of the frame with respect to the topocentric frame, and the spectral resolution. For the estimates below, we assume the maximum velocity offset: 33.4 $\mathrm{km\,s^{-1}}$. This offset

Table 2: Minimum Recommended Switching Periods for Observations Without Doppler Tracking

	Total Power No Noise Diode	Total Power Noise Diode	Frequency Switched No Noise Diode	Frequency Switched Noise Diode
	`tp_nocal`	`tp`	`sp_nocal`	`sp`
Mode	(s)	(s)	(s)	(s)
(1)	(2)	(3)	(4)	(5)
1	0.0005	0.0100	0.3200	0.3300
2	0.0014	0.0280	0.3200	0.3480
3	0.0020	0.0400	0.3200	0.3600
4	0.0100	0.0280	0.3200	0.3480
5	0.0199	0.0559	0.3200	0.3759
6	0.0301	0.1118	0.3200	0.4318
7	0.0102	0.0524	0.3200	0.3724
8	0.0203	0.1049	0.3200	0.4249
9	0.0301	0.2097	0.3200	0.5297
10	0.0056	0.2237	0.3200	0.5437
11	0.0112	0.4474	0.4474	0.8948
12	0.0280	0.8948	0.8948	1.7896
13	0.0447	1.7896	1.7896	3.5791
14	0.0671	3.5791	3.5791	7.1583
15	0.0056	0.4474	0.4474	0.8948
16	0.0112	0.8948	0.8948	1.7896
17	0.0336	1.7896	1.7896	3.5791
18	0.0447	3.5791	3.5791	7.1583
19	0.0895	7.1583	7.1583	14.3166
20	0.0051	0.0280	0.3200	0.3480
21	0.0101	0.0559	0.3200	0.3759
22	0.0301	0.1118	0.3200	0.4318
23	0.0405	0.2237	0.3200	0.5437
24	0.0755	0.4474	0.4474	0.8948
25	0.0070	0.0388	0.3200	0.3588
26	0.0141	0.0777	0.3200	0.3977
27	0.0398	0.1553	0.3200	0.4753
28	0.0544	0.3107	0.3200	0.6307
29	0.1010	0.6214	0.6214	1.2428

Col (1): VEGAS mode
Col (2): Recommended minimum switching period for total power observations without the noise diode (`tp_nocal`) and without Doppler tracking. This value is equivalent to the hardware exposure value for VEGAS.
Col (3): Recommmended minimum switching period (`swper`) for total power observations with the noise diode (`tp`) and without Doppler tracking. This switching period will result in less than 10% of your data being blanked.
Col (4): Recommended minimum switching period (`swper`) for frequency switched observations without the noise diode (`sp_nocal`) and without Doppler tracking. This switching period will result in less than 10% of your data being blanked.
Col (5): Recommended minimum switching period (`swper`) for frequency switched observations with the noise diode (`sp`) and without Doppler tracking. This switching period will result in less than 10% of your data being blanked.

is the maximum offset between the LSRK and topocentric frames and is sufficiently similar to the 30 $\mathrm{km\,s^{-1}}$offset from topocentric for the barycentric frame that we use the same value for both cases. We do not consider the more restrictive, but infrequently used, frames of Galactocentric, Local Group, and CMB, where the velocity offset can be up to ∼220, ∼308, and ∼370 $\mathrm{km\,s^{-1}}$, respectively.

The velocity of the source is

$$v = v_{frame} \cos\theta \tag{7}$$

where v_{frame} is the velocity of the frame with respect to Earth and θ is the angle between the apex of the coordinate system and the object. Taking the derivative and assuming the worst possible case ($\sin\theta = 1$),[1]

$$\Delta v = v_{frame} \Delta\theta \tag{8}$$

where Δv is the change in velocity and $\Delta\theta$ is the change in angle.

We estimate $\Delta\theta$ in two important cases: 1) on-the-fly mapping and 2) pointed high spectral line resolutions. In the on-the-fly mapping case, the mapping rate, R, is

$$R = \frac{\theta_N}{n_{os} t_{int}} \tag{9}$$

where θ_N is the nyquist sampling rate ($= \lambda_{obs}/(2D)$), D is the diameter of the telescope (100m for the GBT), n_{os} is the oversampling in the scanning direction, and t_{int} is the integration time (Mangum et al. 2007). The change in angle for one switching period is

$$\Delta\theta = \frac{\theta_N}{n_{os} t_{int}} t_{swper} = \frac{c\, t_{swper}}{2D\nu t_{int}} \tag{10}$$

Here ν is the observing frequency. Substituting this equation into Equation 8 and converting to frequency, we obtain

$$\Delta\nu = \left(\frac{v_{frame}}{2D}\right)\left(\frac{t_{swper}}{t_{int}}\right)\left(\frac{1}{n_{os}}\right). \tag{11}$$

The Doppler tracking at the GBT is typically set so that the LO1 frequency updates if the frequency changes by more than 1/100 of a channel in a switching period, i.e.,

$$\Delta\nu > \Delta\nu_{chan}/100 \tag{12}$$

where $\Delta\nu_{chan}$ is the channel size (see Table 1). Using Equation 11, we find that for VEGAS channel sizes less than

$$\Delta\nu_{chan} < 100 \frac{v_{frame}}{2D}\left(\frac{t_{swper}}{t_{int}} \frac{1}{n_{os}}\right) \tag{13}$$

the LO1 blanking will occur potentially once every switching cycle.

Figure 3 shows the relationship between the spectral resolution at which Doppler Tracking be-

[1]The typical case is similar to the worst case because the average value of the sine function over a single period is 0.64.

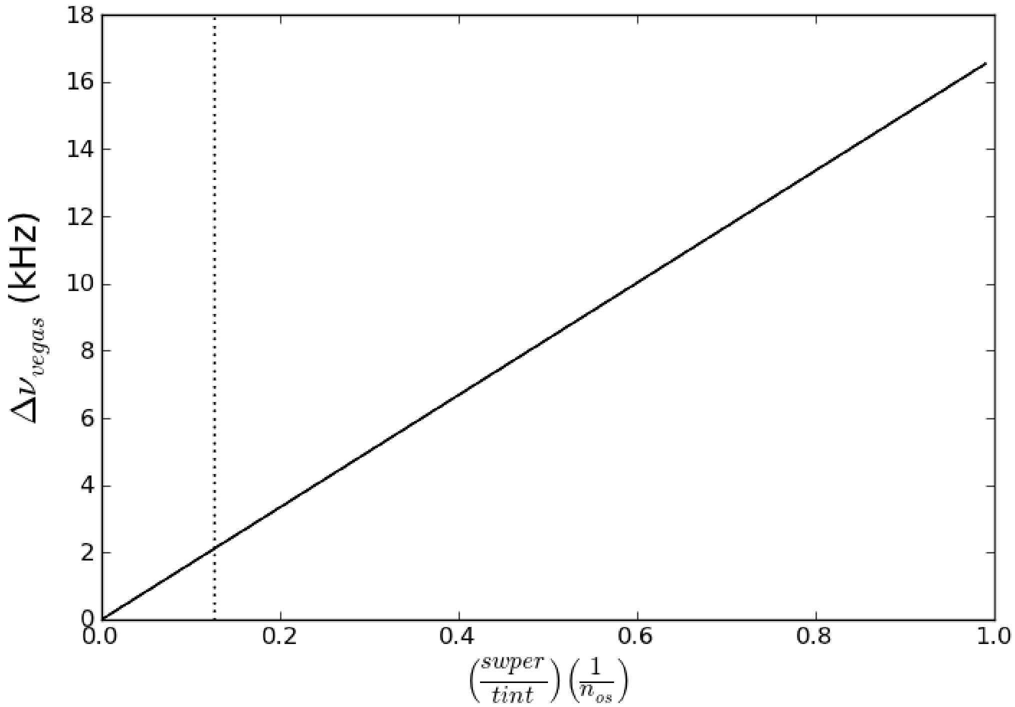

Figure 3: For on-the-fly mapping observations, the spectral resolution where Doppler blanking occurs every switching cycle as a function of the mapping parameters (swper, tint, and oversampling factor). The common case where swper/tint = 1/4 and n_{os} = 2 is shown as a dotted line.

comes important and the quantity in paranthesis in Equation (13). In Table 3, we give recommended switching periods for Doppler tracking for the typical mapping case where $t_{swper}/t_{int} = 1/4$ and $n_{os} = 2$ to blank less than 10% of one's data for total power observations and less than 10% of the first state of the switching cycle for frequency switched observations.

For pointed observations, the rate of change in angle is $15\,\mathrm{deg\,hr^{-1}} = \pi/6.0\,\mathrm{radian\,hr^{-1}} = 1.45 \times 10^{-4}\,\mathrm{radian\,s^{-1}}$. The change in the angle is then just $\Delta\theta = 1.45 \times 10^{-4}\,\mathrm{radian\,s^{-1}}\,\mathrm{t_{swper}}$. Using Equation 8 and requiring a frequency accuracy of a hundredth the channel size, we find that

$$\Delta\nu_{chan} < 100\frac{\nu}{c}v_{frame}\,1.45 \times 10^{-4}\,\mathrm{radian\,s^{-1}}\,t_{swper}. \tag{14}$$

Here the relevant frame is the topocentric frame where $v_{frame} = 0.5\,\mathrm{km\,s^{-1}}$. Figure 4 shows this quantity plotted as a function of switching period for several fiducial frequencies. Blanking becomes important when

$$\nu * t_{swper}[\mathrm{GHz\,s}] > \frac{\Delta\nu_{chan} * c}{10^{11} * v_{frame} * 1.45 \times 10^{-4}\,\mathrm{radian\,s^{-1}}}. \tag{15}$$

Table 4 lists the frequency above which blanking due to Doppler tracking becomes important for

Table 3: Minimum Recommended Switching Periods for Mapping Observations with Doppler Tracking

	Total Power No Noise Diode	Total Power Noise Diode	Frequency Switched No Noise Diode	Frequency Switched Noise Diode
	`tp_nocal`	`tp`	`sp_nocal`	`sp`
Mode	(s)	(s)	(s)	(s)
(1)	(2)	(3)	(4)	(5)
1	0.0010	0.0100	0.3200	0.3300
2	0.0028	0.0280	0.3200	0.3480
3	0.0040	0.0400	0.3200	0.3600
4	0.0114	0.0280	0.3200	0.3480
5	0.0227	0.0559	0.3200	0.3759
6	0.0357	0.1118	0.7600	1.5200
7	0.0128	0.0524	0.3200	0.3724
8	0.0256	0.1049	0.7600	1.5200
9	0.0406	0.2097	0.7600	1.5200
10	0.0168	0.2237	0.7600	1.5200
11	0.0336	0.4474	0.7600	1.5200
12	0.0727	0.8948	0.8948	1.7896
13	0.1342	1.7896	1.7896	3.5791
14	0.2461	3.5791	3.5791	7.1583
15	0.0280	0.4474	0.7600	1.5200
16	0.0559	0.8948	0.8948	1.7896
17	0.1230	1.7896	1.7896	3.5791
18	0.2237	3.5791	3.5791	7.1583
19	0.4474	7.5383	7.1583	14.3166
20	0.0065	0.0280	0.3200	0.3480
21	0.0129	0.0559	0.3200	0.3759
22	0.0357	0.1118	0.7600	1.5200
23	0.0517	0.2237	0.7600	1.5200
24	0.0979	0.4474	0.7600	1.5200
25	0.0090	0.0388	0.3200	0.3588
26	0.0180	0.0777	0.7600	1.5200
27	0.0476	0.1553	0.7600	1.5200
28	0.0699	0.3107	0.7600	1.5200
29	0.1320	0.6214	0.7600	1.5200

Col (1): VEGAS mode
Col (2): Recommended minimum switching period (`swper`) for Doppler-tracked, total power on-the-fly maps with no noise diode (`tp_nocal`). These values will yield less than 10% blanking overall. These values assume that the maps are sampled at twice Nyquist in the scanning direction and that there are four integrations per switching period.
Col (3): Recommmended minimum switching period (`swper`) for Doppler-tracked, total power on-the-fly maps with the noise diode (`tp`). These values will yield less than 10% blanking overall. These values assume that the maps are sampled at twice Nyquist in the scanning direction and that there are four integrations per switching period.
Col (4): Recommended minimum switching period (`swper`) for Doppler-tracked, frequency switch observations with the noise diode turned off (`sp_nocal`). These values will yield less than 10% blanking in the first state of the switching cycle as well as less than 10% blanking overall. This switching period will result in less than 10% of your data being blanked. These values assume that the maps are sampled at twice Nyquist in the scanning direction and that there are four integrations per switching period.
Col (5): Recommended minimum switching period (`swper`) for Doppler-tracked, frequency switch observations with the noise diode turned on (`sp`). These values will yield less than 10% blanking in the first state of the switching cycle as well as less than 10% blanking overall. These values assume that the maps are sampled at twice Nyquist in the scanning direction and that there are four integrations per switching period.

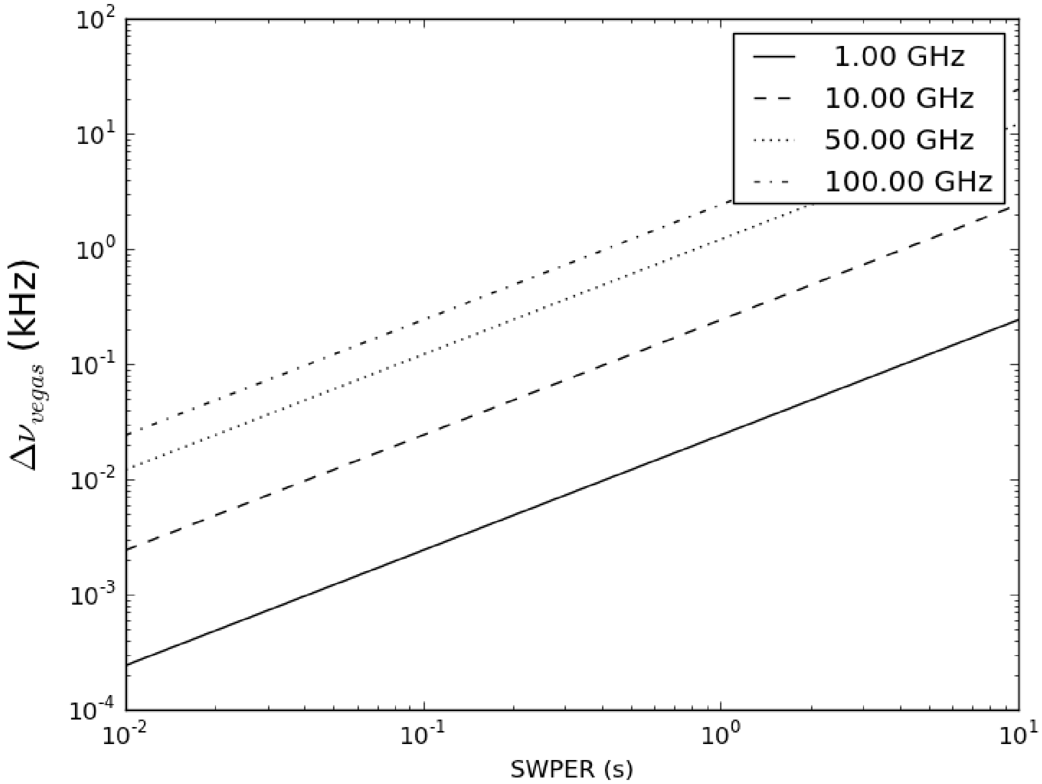

Figure 4: For pointed observations, the spectral resolution where Doppler tracking occurs every switching cycle as a function of the switching period.

pointed observations and gives recommended minimum switching periods for total power to avoid blanking more than 10% of the data and for frequency switched observations to avoid blanking more than 10% of the first state of the switching cycle. For frequencies below the minimum frequency, use the recommended minimum switching periods in Table 2.

To completely avoid blanking due to Doppler updates, you can turn off Doppler tracking by selecting the topocentric reference frame *and* not specifying any velocities in your catalog. If you do this, watch the LO1 CLEO screen carefully to make sure that the LO1 is not updating to confirm that Doppler tracking is not occurring. It is currently possible with additional effort on the user's part to correct for the Doppler motion of a source offline using GBTIDL; improved methods are under development.

REFERENCES

Mangum, J. G., Emerson, D. T., & Greisen, E. W. 2007, A&A, 474, 679

Table 4: Minimum Recommended Switching Periods for Pointed Observations with Doppler Tracking

	Total Power No Noise Diode		Total Power Noise Diode		Frequency Switched No Noise Diode		Frequency Switched Noise Diode	
	tp_nocal		tp		sp_nocal		sp	
	ν_{min}	swper	ν_{min}	swper	ν_{min}	swper	ν_{min}	swper
Mode	GHz	(s)	GHz	(s)	GHz	(s)	GHz	(s)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	> 115	0.0005	> 115	0.0100	> 115	0.7600	> 115	1.5200
2	> 115	0.0014	> 115	0.0280	> 115	0.7600	> 115	1.5200
3	> 115	0.0020	> 115	0.0400	> 115	0.7600	> 115	1.5200
4	> 115	0.0100	> 115	0.0280	> 115	0.7600	> 115	1.5200
5	> 115	0.0199	> 115	0.0559	> 115	0.7600	> 115	1.5200
6	> 115	0.0301	> 115	0.1118	> 115	0.7600	> 115	1.5200
7	> 115	0.0102	> 115	0.0524	> 115	0.7600	> 115	1.5200
8	> 115	0.0203	> 115	0.1049	> 115	0.7600	> 115	1.5200
9	> 115	0.0301	> 115	0.2097	> 115	0.7600	59.6	1.5200
10	> 115	0.0056	> 115	0.2237	> 115	0.7600	54.4	1.5200
11	> 115	0.0112	33.1	0.4474	33.1	0.7600	16.5	1.5200
12	> 115	0.0280	8.3	0.8948	8.3	0.8948	4.1	1.7896
13	82.7	0.0447	2.1	1.7896	2.1	1.7896	1.0	3.5791
14	27.6	0.0671	0.5	3.5791	0.5	3.5791	0.3	7.1583
15	> 115	0.0056	33.1	0.4474	33.1	0.7600	16.5	1.5200
16	> 115	0.0112	8.3	0.8948	8.3	0.8948	4.1	1.7896
17	110.3	0.0336	2.1	1.7896	2.1	1.7896	1.0	3.5791
18	41.3	0.0447	0.5	3.5791	0.5	3.5791	0.3	7.1583
19	10.3	0.3800	0.1	7.5383	0.1	7.1583	0.1	14.3166
20	> 115	0.0051	> 115	0.0280	> 115	0.7600	> 115	1.5200
21	> 115	0.0101	> 115	0.0559	> 115	0.7600	> 115	1.5200
22	> 115	0.0301	> 115	0.1118	> 115	0.7600	> 115	1.5200
23	> 115	0.0405	> 115	0.2237	> 115	0.7600	54.4	1.5200
24	> 115	0.0755	33.1	0.4474	33.1	0.7600	16.5	1.5200
25	> 115	0.0070	> 115	0.0388	> 115	0.7600	> 115	1.5200
26	> 115	0.0141	> 115	0.0777	> 115	0.7600	> 115	1.5200
27	> 115	0.0398	> 115	0.1553	> 115	0.7600	89.7	1.5200
28	> 115	0.0544	68.6	0.3107	68.6	0.7600	33.8	1.5200
29	105.5	0.1010	17.1	0.6214	17.1	0.7600	8.6	1.5200

Col (1): VEGAS mode
Col (2, 4, 6, 8): Frequency above which you should use the minimum recommended switching period values in this table. Below this the values in Table 2 are appropriate.
Col (3): Recommended minimum switching period for pointed, Doppler-tracked, total power observations without the noise diode (`tp_nocal`). These values will yield less than 10% blanking overall.
Col (5): Recommended minimum switching period for pointed, Doppler-tracked, total power observations with the noise diode (`tp`). These values will yield less than 10% blanking overall.
Col (7): Recommended minimum switching period for pointed, Doppler-tracked, frequency-switched observations without the noise diode (`sp_nocal`). These values will yield less than 10% blanking in the first state of the switching cycle as well as less than 10% blanking overall.
Col (9): Recommended minimum switching period for pointed, Doppler-tracked, frequency-switched observations with the noise diode (`sp`). These values will yield less than 10% blanking in the first state of the switching cycle as well as less than 10% blanking overall.