Zpectrometer observing technical notes

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These notes are meant to assist with proposal preparation for the Zpectrometer by supplying information on system specifications, overheads, and sensitivity. They will also be made available to GBT proposal referees and the GBT Scheduling Committee.

1 Bandwidth and resolution

The Zpectrometer covers 25.6–37.7 GHz ($z = 2.06$–3.50 for CO $J = 1-0$, 5.12–8.00 for CO $J = 2-1$, 1.35–2.46 for HCN $J = 1-0$, and 3.70–5.92 for HCN $J = 2-1$). It contains four independent sub-bands with a few channels of overlap between each adjacent pair.

The standard frequency resolution is 24 MHz, with frequency resolution constant across all bands. With a 38% fractional bandwidth the velocity resolution changes noticeably from one end of the band to the other. It is possible to push the frequency resolution to 18 MHz at the cost of modest increases in calibration (see below) and processing time. It is also possible to adjust channel center frequencies and the resolution element shape in steps of about 1/3 of the resolution width in post-processing.

2 Observing mode

The Zpectrometer's flat baselines result in part from the switching secondary scheme that Ron Maddalena and others at Green Bank developed, in which the subreflector moves to alternate the optical image of the source on the Ka-receiver's two feed horns. The Zpectrometer continuously differences the signals from these beams, so the source is observed in both subreflector positions. Switching the subreflector alone still leaves ~ 50 mJy of lumpy baseline structure from optical beam imbalance, however. The structure is not sufficiently stable for long deep integrations, but it is stable over minutes. Taking this into consideration, the Zpectrometer's standard observing mode is to switch between a source position and a nearby reference position, with four minutes on each position. Differencing the raw spectra from the two positions removes the optical imbalance to a high degree. The reference position can be true blank sky or it can coincide with a second scientifically interesting target. In the latter case, should both targets be detected, the source target appears as a positive line and the reference target appears as a negative line in the position-differenced spectrum. The strategy of observing target pairs can be generalized to multiple targets that are close to each other on the sky. Naturally, it is necessary to avoid pairing targets whose lines could fall at exactly the same velocity, as they would cancel to an unknown degree in the difference spectrum. We have not quantified how close sources should be on the sky for this observing mode to work, but a scale of degrees seems reasonable, especially at high elevation where the differential pickup should change slowly with position.

The double switching carries a theoretical cost of two in observing time, but in practice nonideal spectral structure overwhelms the theoretical advantage. Figures 1 and 2 illustrate the need for this position switching differencing. All spectra are calibrated for passband gain (see eq. (3); "vector" calibration in GBT jargon); the structure is not specific to the Zpectrometer, but is from the optical imbalance's spectral difference between the two subreflector positions. The middle trace in Figure 1 is the subreflector-switched spectrum toward the Cloverleaf galaxy position. This example has an average offset of about -15 mJy and considerable structure on

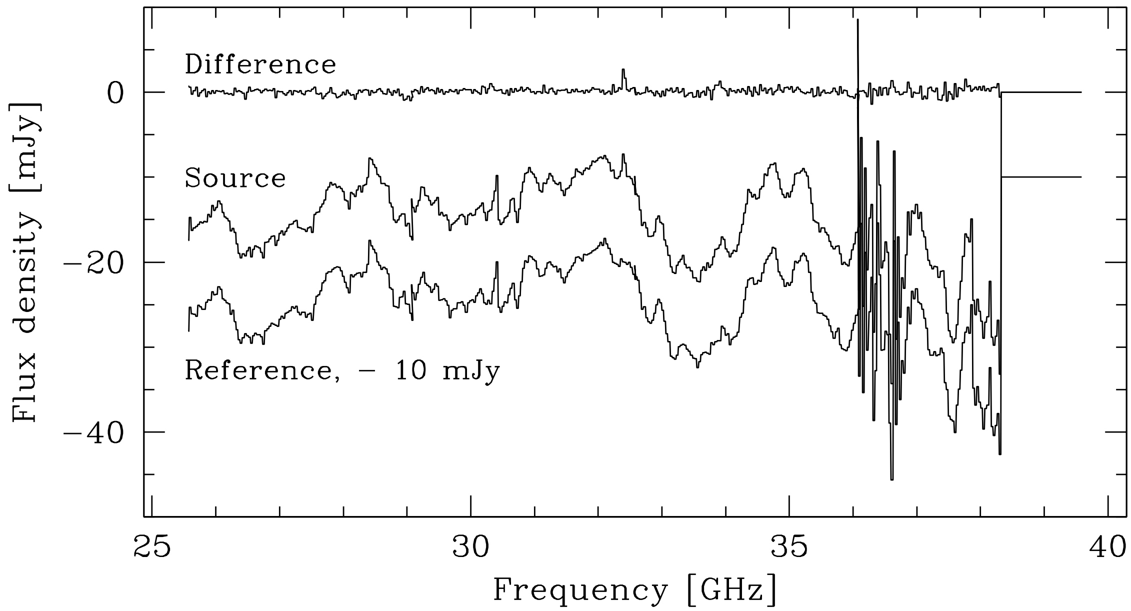

Figure 1: Subreflector-switched and passband gain calibrated spectra of the Cloverleaf galaxy (middle trace, Source), a nearby reference position (bottom trace, Reference, with a −10 mJy offset), and the difference spectrum (Difference, top trace). The individual source and reference spectra show considerable structure.

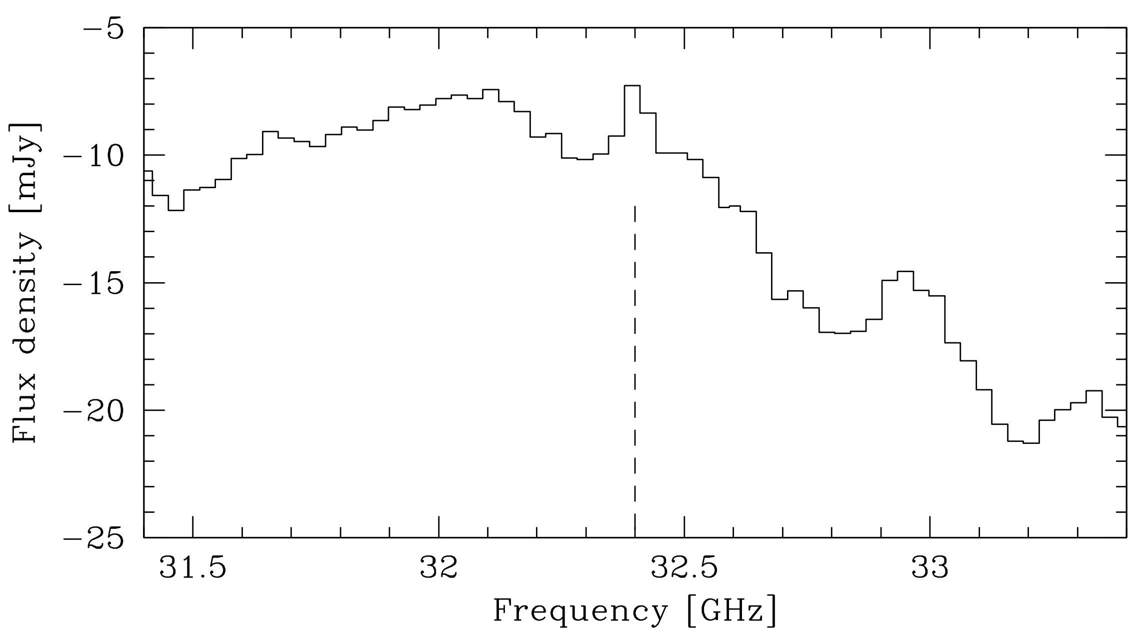

Figure 2: A 2 GHz portion of the Cloverleaf galaxy spectrum from the subreflector-switched source position alone. A dashed line indicates the CO $J = 1-0$ line frequency in the Cloverleaf's observed-frame frequency.

various scales; samples of many spectra show structure with peak to peak values ranging over 70 mJy. (The spiky structure above 36 GHz is due to a lack of calibration tone power at the highest frequencies. This summer we plan to add a filter to cut off response above 37.7 GHz to eliminate the aliasing problem that causes excess noise). The lower trace is the subreflector-switched spectrum toward the reference position near the Cloverleaf, with an artificial offset of -10 mJy to allow comparison with the Cloverleaf spectrum. Both spectra have complex but nearly identical structure. The top trace is the simple difference of the two, showing a flat baseline with the CO line from the Cloverleaf and differential noise between the spectra.

The baseline structure in the spectra is too complex to reliably remove with simple fitting. Figure 2 shows the same data on an expanded scale, with 2 GHz total bandwidth centered on the Cloverleaf CO line.

3 Overheads

3.1 Basic observing overheads

The subreflector switching efficiency is 0.73 at present, with the loss coming from the mechanical transition time between beams. Each telescope slew between pair positions takes $\sim$ 15 s. Software initiation for a scan is $\sim$ 10 s. It is necessary to point and refocus on a nearby quasar after an hour of integration on source to keep the subreflector actuator bearings lubricated. Pointing on a nearby quasar takes about 6 minutes. Although the pointing is generally very good most of the time, within 1/3 beamwidth, the periodic pointing checks are useful checks for wind shake.

A typical observing cycle comprises 7 repetitions $\times$ 2 positions $\times$ 4 minute scans and a pointing cycle. This pattern yields 20.5 minutes of integration on each of the sky and reference positions in a total of 65.5 minutes of elapsed (wall-clock) time for a basic observing efficiency $\eta_{\mathrm{obs}} = 0.62$, as expected from the individual efficiency contributions.

3.2 Session overheads

Observing session overheads include receiver selection, initial slewing and pointing, and calibration. There is no setup or tuning overhead for the Zpectrometer past running an Astrid script to set some switches in the Ka-band receiver. Receiver selection can take from no time at all if the Ka-band receiver is already at focus, to 5–10 minutes. Initial slewing to and pointing on near a calibrator or science target takes 15–30 minutes.

The only overhead unique to the Zpectrometer is a requirement to take a spectrum of a bright quasar (typically 3C48 or 3C286) with known 32 GHz flux each session. A contemporaneous spectrum provides accurate passband and flux calibration and system diagnostics. One spectrum with a few minutes of integration time per observing session is sufficient. Source, reference, and calibration spectra combine to make a fully calibrated science spectrum

$$S_\nu(f) = \frac{R_{\mathrm{source}}(f) - R_{\mathrm{reference}}(f)}{R_{\mathrm{calibrator}}(f)}\, S_{\nu,\,\mathrm{calibrator}}(f = 32\ \mathrm{GHz}) \tag{1}$$

where $R(f)$ is the accumulated raw spectrum for a given position. Slewing and pointing before and after calibrator observations takes a total of 20–30 minutes.

Shutdown procedures take a minute at most. Overall session overheads are thus somewhere between 30 and 60 minutes.

3.3 Super-session overheads

Every one or two weeks it is advisable to make a receiver and correlator internal phase calibration, which takes about 20 minutes for 24 MHz resolution and 30 minutes for 18 MHz resolution. In contrast to the observations of passband and flux calibrators, these phase calibration datasets can be shared between projects.

4 Sensitivity

In winter weather conditions (see related web link in §6), typical system temperatures are $\sim 45\,\mathrm{K}$. (As a practical matter for observing, wind is often more of a problem than opacity.) This value is representative and varies with frequency. The Zpectrometer continually monitors and logs an internal signal to produce its own T_{sys} estimate; by next winter, we expect that the value will be written into data headers to allow automatic data weighting by T_{sys}.

4.1 Ideal sensitivity

For a double-differenced spectrum from a correlation receiver the theoretical effective rms noise in a signal to noise calculation is

$$\sigma_{\mathrm{K}} = 2\,\frac{T_{\mathrm{sys}}}{\sqrt{B\tau\eta_{\mathrm{obs}}}} \tag{2}$$

where B is the channel's frequency width, τ is the sum of wall-clock integration times on the source and reference positions, and $\eta_{\mathrm{obs}} \approx 0.6$ is the basic observing efficiency discussed in §2. In flux, (2) becomes

$$\sigma_{\mathrm{Jy}} = 1.3\,\frac{T_{\mathrm{sys}}\,[\mathrm{K}]}{\sqrt{B\tau\eta_{\mathrm{obs}}}}\,[\mathrm{Jy}] \tag{3}$$

taking 1.50 K/Jy at 32 GHz from GBT documentation.

4.2 Measured sensitivity

Figure 3 shows that the noise decreases with time following the radiometer equation, but that the noise is higher than equation (3) predicts. Power-law fits to the time sequences show that the noise drops slightly faster than radiometric, but have no correction for decreasing T_{sys} as the source rose during the measurements. We see slopes slightly flatter than theoretical for setting sources. The result implies that Zpectrometer spectral noise integrates down as theoretically expected for integration times to at least eight hours, into the tens of μJy regime, but with a noise that is a factor of two to three higher than predicted by the system temperature alone.

Inspection of the cross-correlation functions suggests that the additional noise comes from fluctuating structures with a few tens of cycles across the spectrum. Such structure is most likely caused by residual imbalance in the receiver front end circuit, or by a cable in the receiver that is known to be defective and that occasionally generates ripple with tens of mJy with an approximately 300 MHz period across the spectrum.

In the case of the Cloverleaf detection, equation (3) predicts $\sigma_{\mathrm{Jy}} = 0.14$ Jy for given the integration time, channel bandwidth, and system temperature. A representative rms across channels is 0.25–0.35 mJy, averaging over various sub-bands and channel ranges within sub-bands. This value includes systematic baseline structure wider than typical lines. It also scales with errors in estimated system temperature and overall flux calibration.

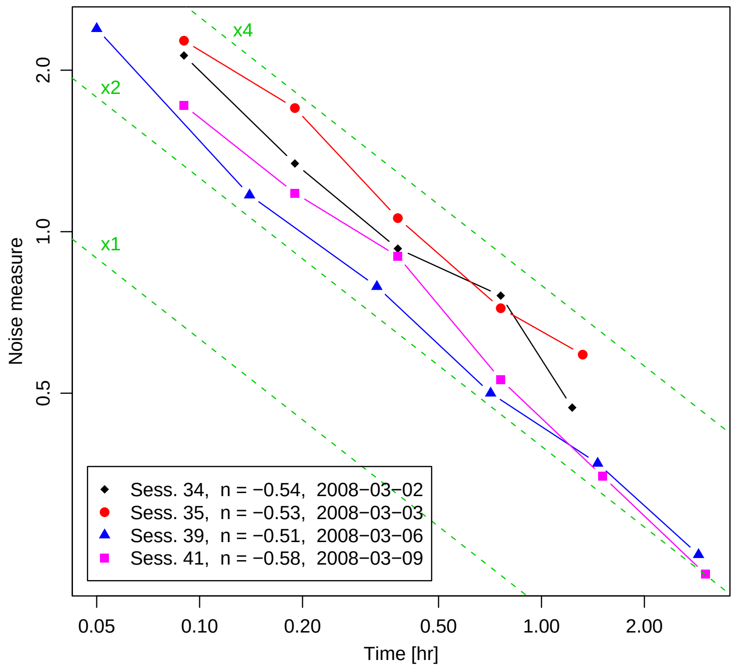

Figure 3: Noise versus integration time for four observing sessions. The dashed lines show the theoretical values from equation (3) scaled by unity, two, and four.

5 Recommendations

For proposal sensitivity estimates, use eq. (3) with $T_{\rm sys} = 45$ K, $B = 24$ MHz, and $\eta_{\rm obs} = 0.6$ for τ the sum of wall-clock seconds on both source and reference positions. If both source and reference targets carry equal scientific weight then the same time includes both targets. Our best advice at present is to multiply σ by a factor of 2 to account for nonideal noise. Consult the GBT documentation for scaling the representative T_{sys} to a specific frequency. In addition, allowing 30–60 minutes for startup and calibration activities and 15 minutes per target pair change gives a conservative but often realistic estimate of global overheads for each session.

6 Links

GBT observation planning guide:
`http://www.gb.nrao.edu/~rmaddale/GBT/ReceiverPerformance/PlaningObservations.htm`

Technical documentation on the Zpectrometer and observing:
`http://www.astro.umd.edu/~harris/kaband/`

Zpectrometer Cloverleaf detection spectrum:
`http://www.gb.nrao.edu/gbt/Zpectrometer/firstDetection.shtml`