Event Horizon Telescope
Memo Series

EHT Memo 2014-ETWG-01

EHT Technical Working Group

LO Frequency for future EHT mmVLBI

Daniel P. Marrone[1], Remo P.J. Tilanus[2,3], Sheperd S. Doeleman[4,5]

Apr 16, 2014 – Version 1.0

[1]*Steward Observatory, Univ. of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA*
[2]*Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands*
[3]*Department of Astrophysics, IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands*
[4]*Massachusetts Institute of Technology, Haystack Observatory, 99 Millstone Rd., Westford, MA 01886, USA*
[5]*Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA*

Document history:

- Feb 25, 2019 – Converted to LaTeX.
- Jan 01, 2014 – Document created.

Contents

1 Fixed LO Frequency

The South Pole Telescope[1] (SPT) is a 10-meter diameter telescope operating at the NSF South Pole research station. The telescope is designed for conducting large-area millimeter and sub-millimeter wave surveys of faint, low contrast emission, as required to map primary and secondary anisotropies in the cosmic microwave background. The SPT is currently being outfitted for participation in future Very Long Baseline Interferometry with the addition of a 230/345 GHz SIS receiver and VLBI equipment. This receiver will be equipped with fixed-tuned Gunn oscillators to generate to Local Oscillator (LO) signal. This mandates the identification of optimal LO frequencies for the EHT. Following from the considerations below, the LO frequencies for EHT observations are determined to be 221.1 GHz and 342.6 GHz.

2 IF Range

The bandwidth of SIS receivers in the 230 and 345 GHz bands has expanded quite rapidly over the past years with an 8 GHz band (4–12 GHz) becoming available at an increasing number of telescopes and with some starting to push towards 16 GHz (2–18 GHz). The EHT experiment will expand from IF bandwidths of 1 GHz (per polarization), in recent observations to two sidebands of 4 GHz, 16 GHz in total for two polarizations, corresponding to a data rate of 64 gbps. The future beam-formed ALMA will be a major component of any future mmVLBI network, hence its properties constitute a natural benchmark for the network as a whole. The ALMA 230 GHz (Band 6) receiver has the following properties: two polarizations of sideband-separating SIS mixers, with an IF range of 5–10 GHz for an LO range of 221–265 GHz. The ALMA 345 GHz (Band 7) receiver is also composed of sideband-separating SIS mixers for two polarizations, with an IF range of 4–8 GHz for LO of 283–365 GHz. To achieve a recorded bandwidth of 16 GHz (64 gigabits-per-second (gbps) when Nyquist sampled and digitized at 2-bit precision), the EHT experiments must record both polarizations and 4 GHz in each sideband. Also, ALMA's current correlator is restricted to an aggregate band of 16 GHz per telescope i.e., a maximum of 64 gbps meaning that it will not benefit from higher data rates such as 128 gbps.

The SPT also uses ALMA-style mixers. The top panels of Figure 1 illustrate their performance across the 230 GHz band. The increase in noise towards both ends of each of the IF ranges shown is apparent. This is more clearly shown in the bottom panel of Figure 1, which shows measurement for a set of ALMA Band 6 cartridges. The figures illustrate that for best performance in a 4 GHz band, ALMA and the SPT will want to operate with an IF range of 6–10 GHz, but that a slightly lower range of 5–9 GHz is likely to be acceptable as well.

Two-sideband VLBI observations place the strongest constraints on the setup at the participating facilities. For a single sideband, different IF ranges can be accommodated as long as the RF band is matched. To record two sidebands, matched IF bands will yield complete RF overlap at all facilities, while inconsistent IF ranges generally force incomplete overlap in one or both sidebands. Table 1 shows the range over which 230 GHz receivers at several EHT observatories perform well. From this table, the best common IF range is bounded by ALMA at the low end (5 GHz), and CARMA prevents pushing above ~9 GHz.

[1]The SPT is a collaboration between the Univ. of Chicago, UC Berkeley, Case Western Reserve University, Univ. of Illinois, and Smithsonian Astrophysical Observatory, and is primarily funded by the NSF.

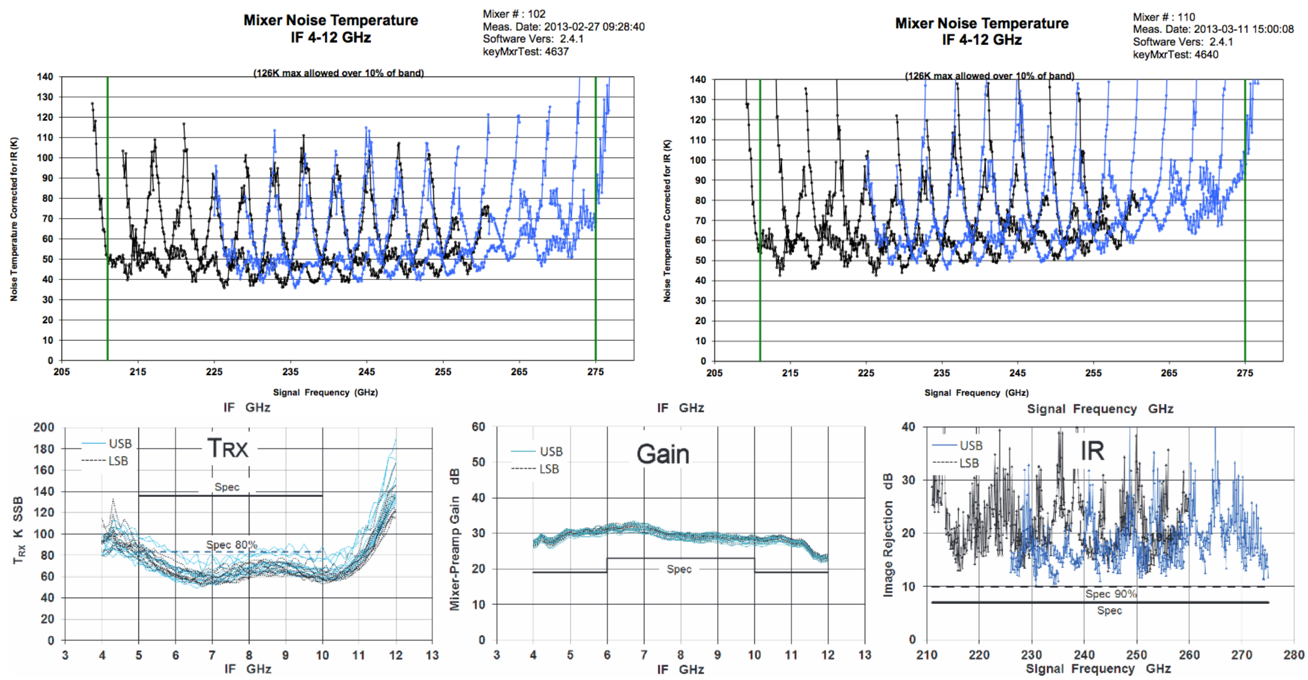

Figure 1: *Top panels:* Noise performance of SPT's two 230 GHz mixers across the 230 GHz window. Lower sideband is shown in black, upper in blue. *Bottom panel:* ALMA band-6 mixers from Kerr et al. (arXiv:1306.6085). These illustrate that the mixers work over the full range of 4–12 GHz, but are optimal in the range of 6–10 GHz.

This 5–9 GHz IF range is different than the 4–8 GHz range at 345 GHz at most observatories, including ALMA, which means that flexibility must be present in downconversion systems. It also conflicts with design decisions for the SMA and NOEMA receiver upgrades, which will split their 8 GHz band into two halves, approximately 4–8 and 8–12 GHz respectively, that will be processed independently. NOEMA will have a beamformer for each section with channelized outputs, which should make it possible to combine channels from both beamformers to effectively store a 5–9 GHz band on the recorder. The SMA is planning two beamformers, which will allow an IF of 5–9 or 6–10 GHz to be recorded, even if the SMA IF is divided into two sections at 8 GHz by the hardware. If a second set of 230 GHz receivers are added to the SMA, then for dual polarization recording the SMA will use one beamformer per receiver and this will limit the SMA phased IF bandwidth to 6 GHz in per polarization (5–8 GHz in both sidebands, or an offset LO giving 4 GHz in one sideband and 2 GHz of RF overlap in the other).

At 345 GHz the 4–8 GHz ALMA IF is more consistent with other observatories. A 5–9 GHz IF appears to be precluded by ALMA hardware. As noted above, since the ALMA specifications will force the 230 GHz IF to be different than 4–8 GHz there must be flexibility in the downconversion systems to be able to translate both 4–8 and 5–9 GHz to the same digitization baseband.

Table 1: IF ranges at 230 GHz

Observatory	IF Range [GHz]	Remarks
IRAM-PV, IRAM-PdB	3.87–11.62	
ALMA, SPT	5–10	
SMT	4–8	To be upgraded to 4-12 GHz
SMA	4–9	To be upgraded to 4-12 GHz
CARMA	2–8.5	IF reaches 9 GHz with degraded performance

Note. — IF range with good mixer performance at a number observatories. Note that the actual receivers may operate over a wider or narrower range.

3 LO frequency for 230 GHz EHT observations

For any IF range, the 230 GHz LO frequency is subject to the following constraints:

- Avoidance of the Galactic CO: (230.5379 300 km/s; i.e. $\sim$ 230.31-230.77 GHz)
- (To a lesser extent) avoidance of Galactic ^{13}CO (220.3987, or 220.18–220.62 GHz)
- Access to the SiO maser (v=1, J=5→4: 215.596 GHz) for VLBI calibration
- Atmospheric transmission.
- (To a lesser extent) Performance current $\frac{1}{4}$-wave plates, which are centered on 225 GHz.
- Access to specific lines for calibration, etc.

Because the long-term solution will be an IF of 5–9 GHz, it is simplest to assume that for the frequency selection unless there is a strong counterargument. We have not identified any reason to hold onto a 6–10 GHz IF option, and so we will simply adopt 5–9 GHz IF in the following.

Nearly all of the constraints above can be satisfied by placing the LO at 221.1 GHz. The RF passband is then 212.1–216.1 GHz and 226.1–230.1 GHz. This tuning is shown in Figure 2. This LO frequency is near the bottom end of the Band 6 LO range, but the bottom panel of Figure1 shows no evidence of degradation in performance in the Band 6 system. While the polarization leakage from the waveplates is not optimized for either sideband (or equalized), the implied leakage is around 4%. It is possibly also useful to have the ^{12}CO line at an IF of 9.44 GHz, within the IF range for the ALMA mixers, so that it may be used for single-dish calibration tasks.

4 LO frequency for 345 GHz EHT observations

The 345 GHz LO is frequency is subject to the following constraints:

- Avoidance of the Galactic CO: (345.7960 300 km/s; i.e. $\sim$ 345.45 346.14 GHz)

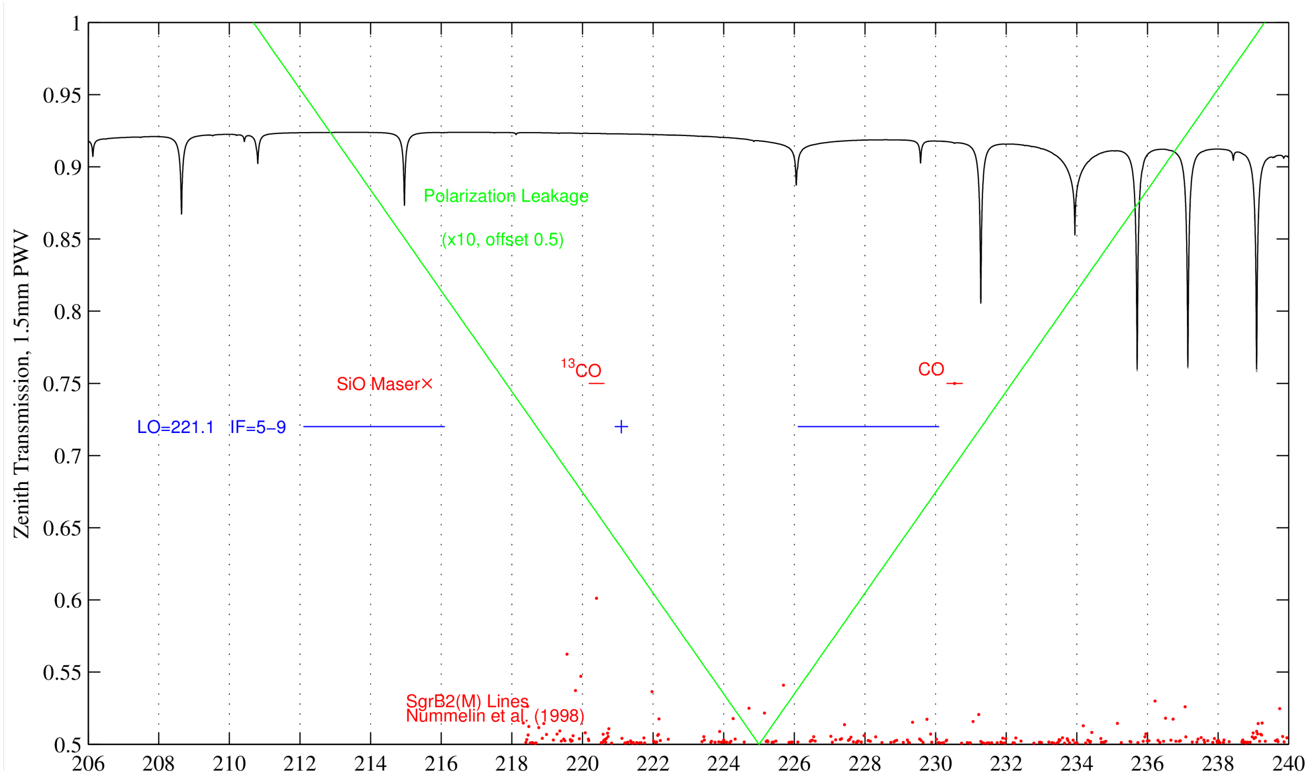

Figure 2: : Frequency coverage for the LO frequency of 221.1 GHz. The atmospheric transmission (black), possible galactic absorption features (red dots), polarization leakage for a subset or EHT stations with 225 GHz waveplates (green), IF range (blue), and CO lines (red horizontal lines, +/-300 km/s) are also shown.

- Atmospheric transmission.
- (To a lesser extent) avoidance of Galactic ^{13}CO (330.5880, or 330.59–330.92 GHz)
- (To a lesser extent) Performance current $\frac{1}{4}$-wave plates, which are centered on 341 GHz.
- Access to specific lines for calibration, etc.

We assume an IF of 4–8 GHz for this band. Considering the CO isotopologues, overall atmospheric transmission in ALMA Band 7 (273–373 GHz), and narrow telluric absorption features (especially those around 333 GHz and 352–353 GHz), the choice of LO is fairly constrained. An LO frequency of 342.6 GHz balances transmission between the sidebands and places the ^{12}CO line just below the USB at an IF of 3.20 GHz. The RF passband is then 334.6–338.6 GHz and 346.6–350.6 GHz. This tuning is shown in Figure 3.

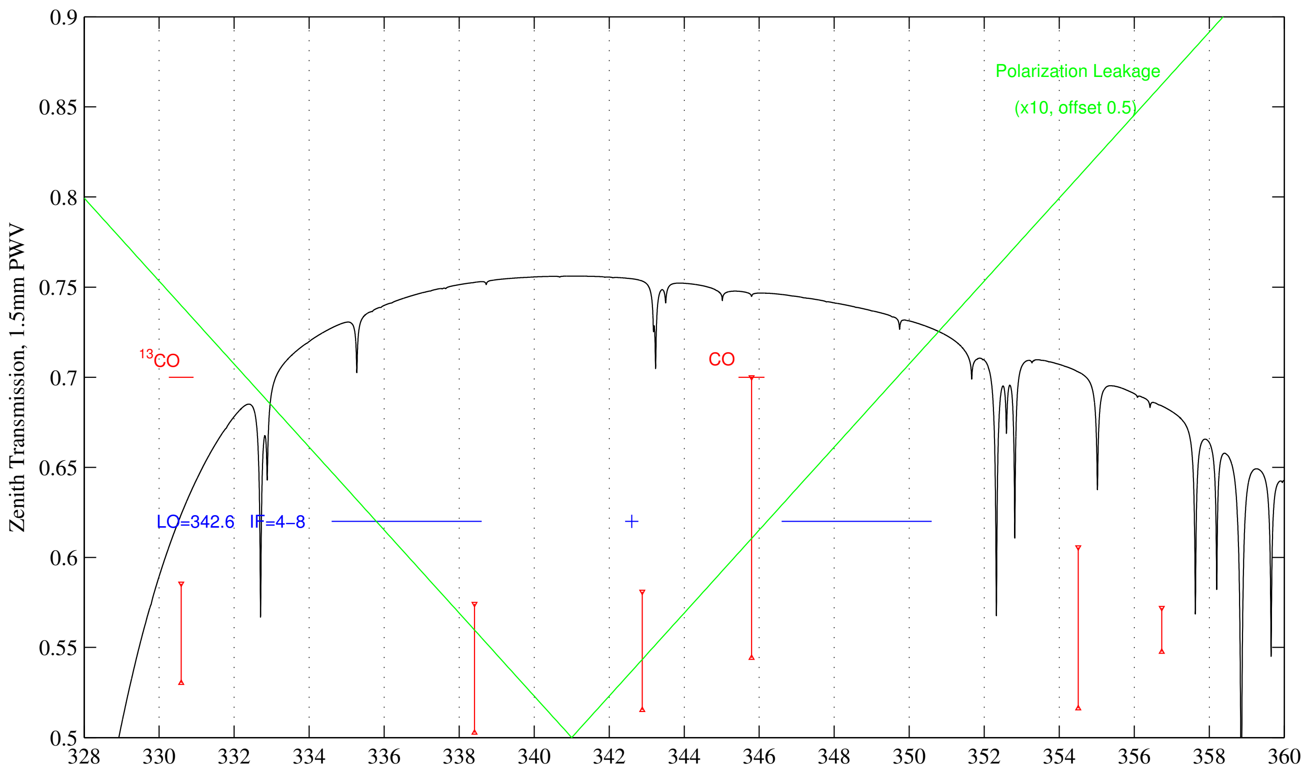

Figure 3: Frequency coverage for an LO frequency of 342.6 GHz. The atmospheric transmission (black), polarization leakage for a subset or EHT stations with 341 GHz waveplates (green), IF range (blue), and CO lines (red horizontal lines, +/-300 km/s) are also shown. Strong galactic lines are shown with red vertical lines, the vertical range of the lines specifies the ratio of antenna temperature in JCMT spectra to the amplitude of ^{12}CO (90 K) in OMC1, all the upper points are the OMC1 temperatures and all the lower points are the IRAS16293-2422 temperatures.