Frequency calibration framework document

L3AB/HIFI/CAL/2003-02, Version 0.2

F.Herpin, D. Teyssier

September 30, 2003

Contents

Reference Documents

RD01: HIFI Calibration Use Cases, ICC/2001-005
RD02: QLA for WBS Use Cases, HIFI-ICC/-00x
RD03: WBS Subsystem SID, HIFI-KOSMA-SP-SA100-001
RD04: HRS Design Description, CESR-HRS-SP-3162-045
RD05: Photometric and spectroscopic calibrations of Herschel instruments with planets and satellites, 2003, Th. Encrenaz et al.
RD06: HIFI Instrument Specification, SRON-G/HIFI/SP/1998-001
RD07: End User Requirements for HIFI Interactive Analysis, ICC/2001-004

1 Introduction

This document is a contribution to the joint common framework document of the HIFI calibration group. Its aim is to reach a common understanding on questions relative to frequencies with HIFI.

In the frequency domain, the observations are smoothed by the effective instrument spectral response, being the combination of several spectral element responses along the detection chain. In this document we describe the principles and parameters we consider are meaningful in the framework of the HIFI frequency calibration. In particular accuracy budgets are derived that should enter the overall calibration error budget to be presented elsewhere. Note that this document should by no mean substitute other documents describing in more details key sub-systems (and their sub-components) such as the Local Oscillator or the backends.

2 Frequencies in the instrument

The HIFI instrument consists of the Focal Plane subsystem (FPU), the Local Oscillator subsystem (LO), the Wide Band Spectrometer (WBS), the High Resolution Spectrometer (HRS) and the Instrument Control Unit (ICU).

The Focal Plane subsystem receives sub-millimetre radiation from the sky (ν_{obs}) and sub-millimetre reference signals from the Local Oscillator (ν_{LO}). It combines these signals in its mixers and produces an Intermediate Frequency (ν_{IF}) signal that is passed on to the WBS and HRS. The WBS and the HRS process the signals and transmit the result to the ICU.

2.1 Heterodyne down-conversion from RF to the first IF

By essence, the heterodyne system produces signal at both the signal frequency and at a mirror frequency (image frequency). Since they are located on either side of the LO frequency, they are usually labelled Upper Side Band (USB) and Lower Side Band (LSB). These frequencies are also called *observed sky frequencies*, i.e. the frequencies of the signal received by the antenna, directly by the *frontend*.

2.1.1 Relation between ν_{obs}, ν_{LO} and ν_{IF}

The heterodyne mixing implies the sum of two (co-)sines which result in the sum frequencies (very high frequency) and the difference frequencies, located around the IF frequency. On HIFI, the IF bandwidth differs between bands 1-5 and bands 6 Low-6 High (6L-6H). A shortest IF bandwidth for bands 6L-6H was finally chosen due to the limited effective bandwidth of the HEB mixers used in these bands. A new bandwidth of 2.4 GHz with an IF at 3.6 GHz is now used, setting frequencies in the [2.4-4.8] GHz domain. Since this range is not adapted to the further down-conversion cascade of the backends (see after), an up-converter is used for bands 6L-6H to rise this range to [5.6-8] GHz.

The following formulas thus apply:

- LO bands 1-5: $\nu_{obs} = k_{sb} \times \nu_{IF} + \nu_{LO}$, where

  - ν_{obs} is the observed rest frequency (corresponding to either $\nu_{rest,USB}$ or $\nu_{rest,LSB}$ in Eqs. 5 and 6 resp.)
  - $k_{sb} = +1$ for upper sideband, $k_{sb} = -1$ for lower sideband
  - ν_{LO} is the LO fixed frequency,
  - ν_{IF} is the frequency at the spectrometer input (4 GHz$< \nu_{IF} <$ 8 GHz)

- LO bands 6L-6H: $\nu_{obs} = k_{sb} \times (\nu_{IF} - \nu_{LO2}) + \nu_{LO}$, where
  - ν_{obs} is the observed rest frequency (corresponding to either $\nu_{rest,USB}$ or $\nu_{rest,LSB}$ in Eqs. 5 and 6 resp.)
  - $k_{sb} = +1$ for upper sideband, $k_{sb} = -1$ for lower sideband
  - ν_{LO} is the LO fixed frequency,
  - ν_{IF} is the frequency at the spectrometer input (5.6 GHz$< \nu_{IF} <$ 8 GHz)
  - ν_{LO2} is the fixed LO frequency in the IF up-converter, nominally 10.4 GHz.

2.1.2 HIFI effective frequency ranges

The HIFI effective frequency ranges for bands 1 to 6H are given in the following table (RD06).

Band	**Frequency Range** (GHz)
1	480-640
2	640-800
3	800-960
4	960-1120
5	1120-1250
6L	1410-1703
6H	1703-1910

Table 1: HIFI Frequency bands

2.1.3 List of LO multiplication matrix

The Local Oscillator Subsystem (LOU) provides the LO signal, produced by the LO Unit, inside the LO Subsystem. The LOU contains the amplifier and multiplier assembly and the mechanical and optical structure necessary to feed the LO signal into the FPU.

The Local Oscillator Source Unit (LSU) provides the *first stage* frequencies (total range 23.57-35.33 GHz, see Table 2) that are then up-converted by a tripler to 71-106 GHz. In a next step this signal is injected in the multiplier chains of the LOU power amplifier for band Ia-VId; the multiplier chains holds between 2 and 4 stage multipliers (see Table 2) to achieve the required RF-coverage between 480 GHz and 1.9 THz. Note that the frequency range of the bands is slightly larger than the LO ones (8 GHz on each side for the bands 1-5, and 4.8 GHz for the bands 6).

L.O. band	first stage [GHz]	up-converter	amplifier [GHz]	multiplier	ν_{LO}-output [GHz]
Ia	27.11-30.67	×3	80-92	$\times 2 \times 3$	488-552
Ib	31.44-35.17	×3	92-106	$\times 2 \times 3$	566-633
IIa	26.96-29.58	×3	80-92	$\times 2 \times 2 \times 2$	647-710
IIb	31.17-33.04	×3	88-99	$\times 2 \times 2 \times 2$	724-793
IIIa	33.63-35.33	×3	92-106	$\times 2 \times 2 \times 2$	807-848
IIIb	23.94-26.47	×3	71-80	$\times 2 \times 2 \times 3$	852-953
IVa	26.86-28.94	×3	80-92	$\times 2 \times 2 \times 3$	967-1042
IVb	29.33-30.92	×3	88-99	$\times 2 \times 2 \times 3$	1056-1113
Va	30.67-35.33	×3	92-106	$\times 2 \times 2 \times 3$	1127-1178
Vb	30.67-35.33	×3	92-106	$\times 2 \times 2 \times 3$	1192-1242
VIa	29.70-33.20	×3	88-99	$\times 2 \times 2 \times 2 \times 2$	1408-1575
VIb	32.05-33.55	×3	92-106	$\times 2 \times 2 \times 2 \times 2$	1528-1696
VIc,d	23.57-26.33	×3	71-80	$\times 2 \times 2 \times 3 \times 2$	1710-1908

Table 2: Multiplier stages for bands I-VI in the LO

2.2 Frequencies in the backends

2.2.1 WBS

The WBS amplifies and conditions the two IF signals from the FPU. It divides the IF band into to 4 sub-bands per polarisation, and down-converts the IF-signal to a lower frequency suitable for injection into a Bragg cell. The bandwidth is 4 GHz.

- **Reminder of AOS principles**

The WBS subsystem is based on 2 acousto-optical 4-channel array-spectrometers including IF-processing and data acquisition. Each spectrometer consists of two separate units:

1. the Optics Unit (WBO). In the WBO the pre-processed IF signals are analysed with acousto-optic technique.
2. Electronics Unit (WBE). The WBE IF section processes the IF signals (4-8 GHz) from the FPU to the four input frequency bands of the WBO ($4 \times 1.6 - 2.6$ GHz). The WBE electronic section controls the subsystem, the data acquisition and the communication with the Instrument computer (ICU).

The principle of an AOS is based on the diffraction of light at ultrasonic waves. A piezzo electric transducer, driven by the RF-signal (from the receiver), generates an acoustic wave in a crystal (the so called Bragg-cell). This acoustic wave modulates the refractive index and induces a phase grating. The Bragg-cell is illuminated by a collimated laser beam. The angular dispersion of the diffracted light represents a true image of the RF-spectrum according to the amplitude and wavelengths of the acoustic waves in the crystal. The spectrum is detected by using a single linear diode array (CCD), which is placed in the focal plane of an imaging optics.

- **Frequencies conversions**

The 2×[4–8] GHz IF band is down-converted to 2×4×[1.6–2.6] GHz by using the following (WBS-internal) LO frequencies:

- 6.6 GHz for the ν_{FPU} =4-5 GHz signal (i.e. $\nu_{IF1} = 6.6 - \nu_{FPU}$)
- 7.6 GHz for the 5-6 GHz signal (i.e. $\nu_{IF1} = 7.6 - \nu_{FPU}$)
- 8.6 GHz for the 6-7 GHz signal (i.e. $\nu_{IF1} = 8.6 - \nu_{FPU}$)
- 9.6 GHz for the 7-8 GHz signal (i.e. $\nu_{IF1} = 9.6 - \nu_{FPU}$)

- **Definition of a channel**

The channel size is in principle defined by the pixel size on the CCD matrix sampling the data. However, the frequency width sampled by this pixel is not necessarily regularly spaced as the diffraction angle created by the acoustic wave is not a linear function of the Bragg cell length. The final spectra is thus reprojected onto a regular frequency grid during the backend calibration. For the HIFI AOS, the total bandwidth is 4 GHz, made of 7650 valid frequency pixels (frequency pixel spacing $\simeq 0.55$ MHz, Nyquist sampling), with a pixel resolution bandwidth ≤ 1.1 MHz. This total width depends on the material in the Bragg cell, as well as its size and the geometrical dimensions involved in the system.

- **Spurious responses (platforming, ghosts,..)**

The total WBS band is composed of 4×1 GHz wide subbands (corresponding to the 4 CCD linear arrays). When co-adding them, the respective subband power levels do not necessarily coincide, resulting in staircase-like baselines also known as *platforming*. The platforming level between subbands is specified to be less than 3 dB on the 1 GHz band. The same applies to the bandpass ripples in each subband. Spurious line signals are also susceptible to affect the signal, like e.g. straylights (specified to be less than 1% of the CCD saturation level) or cross-talk between subbands (specified to be less than 27 dB). Finally, frequency non-linearities are expected in the subbands (should be $< \pm 1$ MHz per band, i.e. $\leq \pm 0.1$ MHz after resampling), as well as power non-linearity (should be $\leq \pm 1$ %).

2.2.2 HRS

The HRS amplifies and conditions the two IF signals from the FPU. It divides the IF band into up to 4 narrow sub-bands per polarisation, placed anywhere in the 4 GHz input bands, and down-converts the IF-signal to a frequency between 1 and 1.5 GHz.

- **Reminder of ACS principles**

The HRS sub-system is made of two boxes: FHHRV and FHHRH (FIRST-HIFI-High-Resolution-spectrometer-Vertical and FIRST-HIFI-High-Resolution-spectrometer-Horizontal resp.). Each box is able to process the RF signal coming from one polarisation of the FPU. Each of these boxes is made of three sections:

1. the IF electronics that down-converts the RF input signal from 4–8 GHz in an acceptable range for the autocorrelator,
2. the digital AutoCorrelator Spectrometer (ACS) section. This section samples and digitizes the analogical signal coming from the IF section, computes the autocorrelation functions of the 8 input bands, sends the autocorrelation functions to the ICU, generates the HK (House Keeping) data and sends them to the ICU,
3. the DC/DC converter providing power.

- **Frequencies conversions**

First of all, the 4–8 GHz signal is amplified, up-converted, and filtered in the 9–10 GHz range with a series of internal LO's (LO_1, LO_2, LO_3 and LO_4, with an image range of 17–25 GHz) as follows:

- the LO_1 at 13.5 GHz (ν_{LO1}) transforms the 4–5 GHz band (ν_{FPU}) in a 1^{st} *IF signal* with new frequency ν_{IF1} between 9 and 10 GHz, i.e. $\nu_{IF1} = |\nu_{LO1} - \nu_{FPU}|$.
- the LO_2 at 14.5 GHz (ν_{LO2}) transforms the 5–6 GHz band (ν_{FPU}) in a 1^{st} *IF signal* with new frequency ν_{IF1} between 9 and 10 GHz, i.e. $\nu_{IF1} = |\nu_{LO2} - \nu_{FPU}|$.
- the LO_3 at 15.5 GHz (ν_{LO3}) transforms the 6–7 GHz band (ν_{FPU}) in a 1^{st} *IF signal* with new frequency ν_{IF1} between 9 and 10 GHz, i.e. $\nu_{IF1} = |\nu_{LO3} - \nu_{FPU}|$.
- the LO_4 at 16.5 GHz (ν_{LO4}) transforms the 7–8 GHz band (ν_{FPU}) in a 1^{st} *IF signal* with new frequency ν_{IF1} between 9 and 10 GHz, i.e. $\nu_{IF1} = |\nu_{LO4} - \nu_{FPU}|$.

The second step is the down-conversion and the filtering of this 1 GHz bandwidth (1^{st} IF) to 1-1.5 GHz (ν_{IF2}) via the LO_5 at 10.5 GHz (ν_{LO5}). We have $\nu_{IF2} = \nu_{LO5} - \nu_{IF1}$.

Finally the LO_6 at 1.25 GHz, also called IRM (Image Rejection Mixer), and made of 2×250 MHz filters, processes this signal and converts it into two 0–250 MHz sub-bands (between 1 and 1.5 GHz) that the ACS can then analyse (upper and lower side-bands: USB, LSB).

- **Definition of a channel**

The band is made of several subbands according to the selected resolution of the HRS. The total number of channels is 4080, with a channel spacing depending on the selected mode (see Table 3). The channel resolution can be seen as a *digital* entity as is solely depends on the clock frequency (here $\nu_{clock} = 550$ MHz – not achieved until now... –), on the lag window used (i.e. *apodisation*) and on the quantisation level. Without any apodisation the half maximum width of a channel is 1.21 × the channel spacing, and the noise equivalent passband is 1 × the channel spacing.

With apodisation by a Hanning function, the channel width becomes 2 × the channel spacing, and the noise equivalent passband 2.66 × the channel spacing.

- **Spurious responses (platforming, ghosts,..)**

As for the WBS, power and frequency non-linearities, as well as platforming and bandpass ripples, may affect the backend response. Specifications for all these issues are the same as for the WBS. Ghosts figures due to the LO elements may also be observed.

Mode	Number of bands /polarisation × bandwidth	Number of lags	Number of offset channels	Spectral res. (kHz) - Hanning type apodisation	Channel spacing (kHz)
High resol.	1 × 250 MHz	1 × 4080	16	135	67
Nominal resol.	2 × 250 MHz	2 × 2040	16	270	134
Low resol.	4 × 250 MHz	4 × 1020	16	539	270
High resol.	4 × 500 MHz	4 ×2× 510	16	1078	540

Table 3: HRS spectrometer modes, sub-band bandwidth and corresponding resolution obtained with Hanning weighting

2.3 Accuracy of the RF frequencies (i.e. accuracy of master LO and up-converter)

The frequency scales of ν_{LO} and ν_{IF} are related to the Master Oscillator (MO) which has a frequency accuracy requirement of 1 part in 10^7 (it will probably be much better). The HRS is directly locked to the MO ; the extra HRS frequency accuracy is 5 kHz. The WBS frequency scale is determined with an internal signal locked to the MO, this means that there is an extra frequency uncertainty (error, i.e. AOS frequency calibration accuracy) in the WBS of 100 kHz.

The band 6 IF up-converter oscillator ν_{LO2} is not locked to the MO. Its frequency will have to be determined by ground characterisation with periodic checking in-flight. The band 6 IF up-converter frequency accuracy is 50 kHz.

The overall HIFI Frequency Accuracy budget is recalled in Table 4.

Assumptions								
Frequency (GHz)	480	640	800	960	1120	1250	1410	1910
LO syst. freq. accuracy (MHz)	0.024	0.032	0.04	0.048	0.056	0.0625	0.0705	0.0955
IF up-convert. freq. acc. (MHz)							0.050	0.050
WBS								
AOS freq. calib. acc. (MHz)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Instr. freq. acc. (MHz)	0.12	0.13	0.14	0.15	0.16	0.16	0.22	0.25
HRS Normal								
HRS freq. acc. (kHz)	5	5	5	5	5	5	5	5
Instr. freq. acc. (kHz)	29	37	45	53	61	68	126	151

Table 4: HIFI frequency accuracy budget.

2.4 Frequency resolution of the instrument (instrument spectral profile)

2.4.1 Definition

The frequency resolution of the whole instrument results from the convolution of the individual resolutions elements of the various components present in the detection chain, principally the LO

Assumptions								
Frequency (GHz)	480	640	800	960	1120	1250	1410	1910
Max. LO linewidth (MHz)	0.080	0.107	0.133	0.160	0.187	0.208	0.235	0.318
IF up-convert. linewidth							0.049	0.049
WBS								
resolution (MHz)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Instr. spec. resol. (MHz)	1.00	1.01	1.01	1.01	1.02	1.02	1.03	1.05
HRS Normal								
resolution (MHz)	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Instr. spec. resol. (MHz)	0.28	0.29	0.30	0.31	0.33	0.34	0.36	0.42
HRS High resolution								
resolution (MHz)	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Instr. spec. resol. (MHz)	0.16	0.18	0.19	0.21	0.23	0.25	0.28	0.35
Instr. resolving power	3.0 10^6	3.6 10^6	4.1 10^6	4.5 10^6	4.8 10^6	5.0 10^6	5.1 10^6	5.4 10^6

Table 5: HIFI spectral resolution budget. Resolutions and linewidths correspond to FWHM.

and the backend respective resolutions.

2.4.2 Resolution accuracy

The overall HIFI frequency resolution budget is recalled in Table 5.

3 Frequency calibration

Frequency calibration measurements address both the calibration of the RF frequency itself and of the frequency resolution (also called here line profile) provided by the instrument. RD01 compiles and describes the objectives of these measurements. We will here give some of the basis required to conduct these calibrations, propose methods and assess time estimates.

3.1 RF Frequency calibration

The fundamental objective of this calibration is to assign of frequency to a given channel number of the considered spectrometer. Since the techniques differ for the respective WBS and HRS backend, we describe both of them separately.

3.1.1 Frequency calibration of the WBS

The overall spectral calibration of the AOS makes use of a COMB measurement providing lines (generally narrow Gaussian lines in regards of the WBS spectral resolution) at known IF frequencies (between 3.9 and 8.1 GHz by steps of 100 MHz). The lines are fitted and their positions in the channel scale are translated into a polynomial function giving frequency in function of pixel numbers. We here do not describe this calibration measurement in further detail and refer to RD02 and RD03 for specified equations and algorithms.

3.1.2 Frequency calibration of the HRS

Due to its digital nature, the HRS frequency calibration is in principle entirely relying on the master oscillator frequency. The frequency conversion table is thus completely defined by the frequency parameters described in Sect. 2.2.

3.1.3 Check of the frequency calibration

Once the frequency calibration procedures described above are complete, the resulting frequency scale needs to be checked against real lines. In this comparison there is still an intrinsic uncertainty related to the assumed rest frequency where a given line is expected. Several spectral database provide tables of these frequencies and the reference for HIFI is still TBD. In order to accurately compare the computed frequency scale to the actual line positions, line profiles should likely be symmetric to allow easy fitting of template profiles.

Line shapes

For the purpose of fitting line shapes, we define the profiles via their centroid frequency ν_0, width at half intensity b (FWHM), and, if necessary, their line peak I_0. For pressures in the ranges 10-1000 mbar, the lines are broadened by pressure effects and can be modelled with a Van Vleck - Weisskopf (VVW) profile given by:

$$\mathcal{F}_{VVW}(\nu,\nu_0,b) = \left(\frac{\nu}{\nu_0}\right)^2 \frac{b}{\pi}\left[\frac{1}{(\nu-\nu_0)^2+b^2}+\frac{1}{(\nu+\nu_0)^2+b^2}\right] \tag{1}$$

which can be reduced to a Lorentzian for $(\nu - \nu_0) << \nu_0$ and $0 << \nu_0$:

$$\mathcal{F}_L(\nu,\nu_0,b) = \frac{b}{\pi}\frac{1}{(\nu-\nu_0)^2+b^2} \tag{2}$$

When the pressure gets very low the Doppler effect due to the random thermal molecular motion dominates the line broadening and the profile is given by a Gaussian:

$$\mathcal{F}_G(\nu,\nu_0,b) = \frac{1}{b}\sqrt{\frac{4\ln 2}{\pi}}\exp\left[-\left(\frac{\nu-\nu_0}{b}\right)^2 4\ln 2\right] \tag{3}$$

The combined picture of a simultaneously Doppler and pressure broadened line profile has been proposed (Voigt profile) but we do not consider it here.

Pre-launch calibration

On the ground, this calibration measurement can be performed using a gas cell which provide spectral lines of well-known profiles. The profile shapes depend on the pressure applied to the sample. In the current plans, lines of OCS, N_2O and CO (and methanol CH_3OH, TBC) are expected to be available. At the pressures of interest (10-100 mbar), the lines are well approximated by VVW or Lorentzian profiles.

The gas cell measurements will be performed against an external hot/cold switch load providing a background contrast of order 200 K. This allows very high signal-to-noise spectra in short integration times (typically $S/N \sim 500$ in 1 sec. at 500 GHz in a 1.1 MHz resolution element). Since absolute photometric calibration is not of concern here, one could easier calibrate this modulated spectra against the internal load, or against the same external hot/cold observed through an empty cell.

In order to perform of the fits described above, line should preferably not be saturated. The error made on the retrieved profile parameters (e.g. FWHM and centroid) can not be easily expressed as a function of the input spectra noise $\sigma_{\rm th}$. It is however questionable whether the fit error on e.g. the line position can indeed achieve the precision required by the instrument specifications (see Sect. 2.3). **[Comments on that ?]**

In-orbit calibration

In orbit, the same principles as for the gas cell can be used, where a adequate spectra needs to be fitted with one of the template profile. Preference should be given to symmetric Gaussian profiles (Eq. 3) of reasonable FWHM. Again, absolute photometric calibration is not of concern. Sources with a rich spectrum could be of interest since *(i)* they are usually compact (permitting the use of double beam switching observations), and *(ii)* they would allow a frequency scale check across the entire bandwidth. Among the potential candidates are:

- circumstellar envelopes: CO (and other) lines in AGB envelopes can exhibit simple profiles, although not often either Gaussian or narrow. They should only be used if accurate models of their spectral profile is available.
- ISM sources: ISM sources such as dark clouds, Hot cores or Photon Dominated Regions (PDRs) are one of the most likely candidates to provide narrow lines with simple shapes. For the sake of efficiency, hot objects should be preferred as they will provide the largest lines (and the richest spectra) in the submm. For a line of 10 K in a 1.1 MHz resolution element, 7 sec. (resp. 74 sec.) are required at 500 GHz (resp. at 1.9 THz) to reach a S/N of 50 (resp. 20) in the double switching mode (overheads accounted). These times are about 3 times larger if observing with the HRS in the normal resolution mode (see table 3).
- Planetary atmosphere lines: atmospheric lines of planets could also be of interest. The probed line profiles will depend on the species as different pressures apply to the different layers associated to a given molecule and transition. Absorption lines can be significantly broad, while emission lines are generally narrower. An overview of the expected lines is given in RD05. It shows that CO and H_2O lines of at least 10-20 K (much stronger lines are expected though) are present in the atmospheres of Mars, Jupiter, Saturn, Uranus and Neptune, so reasonable integration times should also suffice to conduct a meaningful calibration.

3.2 Frequency resolution calibration

This calibration consists in measuring the instrument frequency resolution for each of the backends. If possible, one would also like to assess the channel profile and compare it to the expected one.

3.2.1 Frequency resolution of the WBS

The spectral resolution of spectra obtained with the WBS is measured simultaneously with the frequency scale via the COMB measurement described above. The number of channels between two peaks of the COMB (of known frequency separation) translates into the width of the resolution element. See RD02 and RD03 for more details.

3.2.2 Frequency resolution of the HRS

The HRS frequency resolution is in principle completely determined by the sampling clock speed, as well as by lag function applied for the windowing (generally Hanning windowing). We refer to RD04 for further details.

3.2.3 Check of the frequency resolution

Such checks imply the use of a line generator providing signal narrower than the resolution element to be studied (TBC). While this is likely possible in the laboratory, it is not clear at all whether such narrow lines can be found in space. This check may thus be restricted to the pre-launch calibration. TBFinished **[What more can we say here ?]**

3.3 Long-term measurements

Additional to the frequency calibration is the need for regular checks of the instrument behaviour and performances in the frequency domain. To this purpose a set of so-called *standard spectra* has to be built, which serves as a comparison reference in the course of the mission. Up to the scientific validation phase, this dataset will likely consists of spectra compiled on ground-based and spaceborne observatories. During the mission the database will be updated by spectra observed by HIFI itself and concurrently serve the purpose of health monitoring.

Ideally, the dataset would sample template profiles of different natures, including e.g. the line shapes described above, but also flat-topped profiles, two-horns profiles, large spectral wings, etc. Sources of any category may be of interest. Analysis of the HIFI data against these reference spectra is described by the corresponding Use Cases in RD01.

4 Conversion to velocities

4.1 The velocity reference frames

The observer is interested in having the data expressed in a rest frame appropriate for his/her source. The rest frame may be:

- the instrument rest frame
- the heliocentric rest frame
- the Local Standard of Rest (LSR)
- any other rest frame, for example the rest frame of a particular solar system object, planet or comet.

4.2 Conversion equations

4.2.1 Velocity scale

The radial velocity difference between the satellite/instrument rest frame (V_{sat}) and the required astronomical rest frame (V_{rest}) is given by:

$$\Delta V = V_{rest} - V_{sat} \tag{4}$$

with $V_{rest} = V_{Earth} - V_{LSR}$. Of course other reference frames than the LSR can be considered.

The rest frequencies for the USB and LSB thus write:

$$\nu_{rest,USB} = \nu_{USB}\left(1 - \frac{\Delta V}{c}\right) \tag{5}$$

$$\nu_{rest,LSB} = \nu_{LSB}\left(1 - \frac{\Delta V}{c}\right) \tag{6}$$

Strictly speaking, these formula apply to the on the band center frequency only and assume the usual non-relativistic convention (radio convention here, these are not correct anymore for galaxies with typically $v \geq 3000$km/s).

The translation of channel numbers into frequencies and velocities is given in the *End user requirements* document (RD07), but are recalled here for the sake of completeness. In the chosen rest frame, and adopting the convention introduced above, the conversion between frequency and velocity for a channel i is:

$$V(i) = V_{source} - c\frac{\nu_{rest}(i) - \nu_{rest}}{\nu_{rest}} \tag{7}$$

where V_{source} is the source radial velocity in the rest frame.

4.2.2 Velocity resolution

Following the convention considered above, the velocity resolution can be approximated by (this is only valid for the channel of frequency ν):

$$\frac{\Delta v}{c} = \frac{\Delta \nu}{\nu} \tag{8}$$

with $\Delta\nu$ the channel spacing, ν the frequency, Δv the velocity resolution, and c the speed of light.

5 Change record

- Version 0.1: first draft of the document
- Version 0.2: Re-organize document with minor content update and new tables. Add new section 3. Complete section 4.