Heterodyne receivers in space: lessons learned from Herschel/HIFI

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Disclaimer and Outline

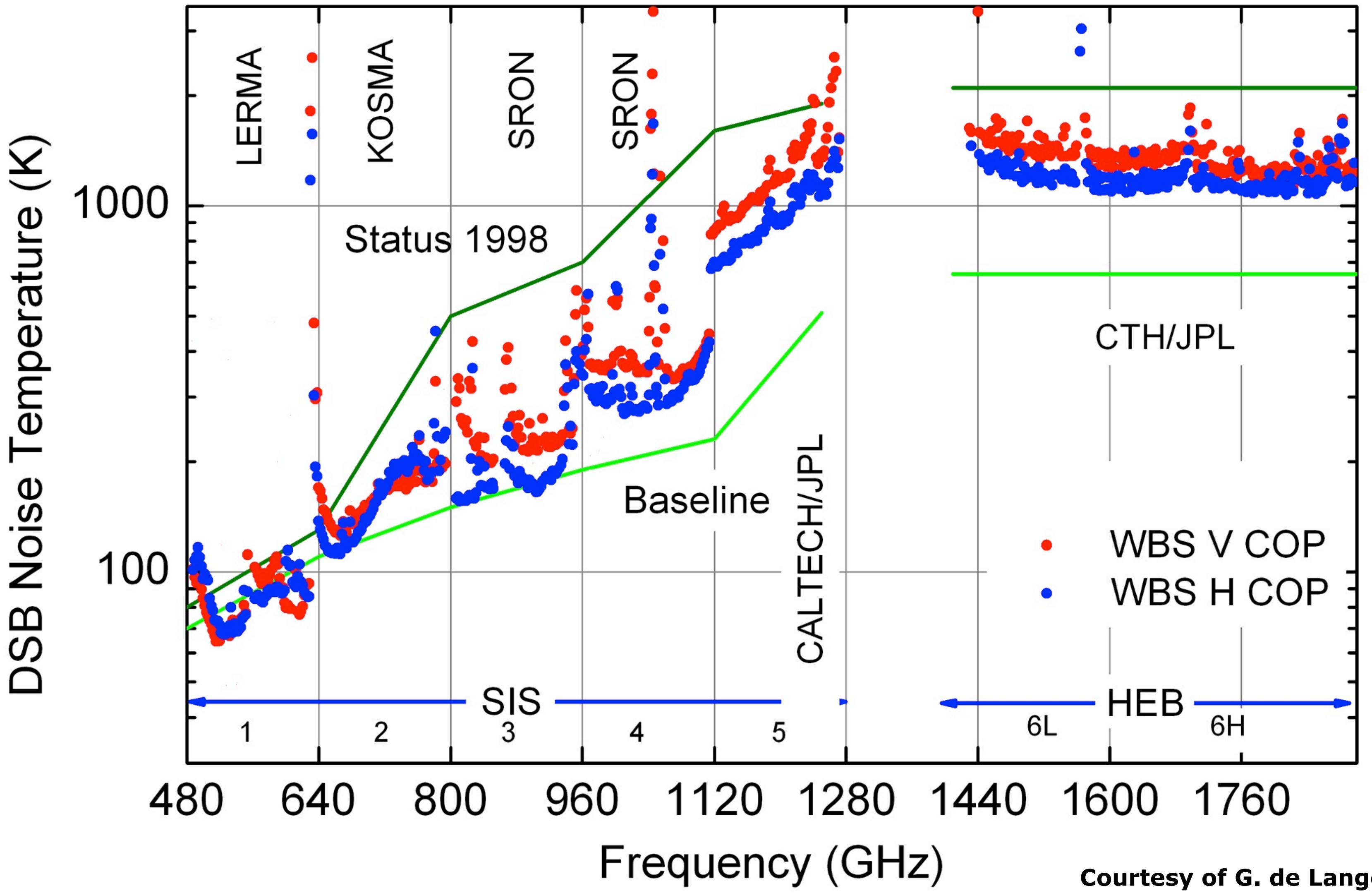
Disclaimer

- Most of this will not be new to many of you
- My own experience from an operational and end-user astronomer perspective

Outline

1. Quick reminder of HIFI performances
2. Local Oscillator spectral purity
3. Detection chain stability
4. Optical and Electrical standing waves
5. Mixer sideband gain ratio
6. Autonomous operations at Lagrange point 2
7. Conclusions

HIFI in-orbit performance (1)



Courtesy of G. de Lange (SRON)

HIFI in-orbit performance (2)

- ***Allan times***

Band	Total power	Spectro	Differential
Best band (5a)	~20 sec	90-130 sec	1800 sec
Worse band (HEBs)	3-5 sec	15-20 sec	500-700 sec

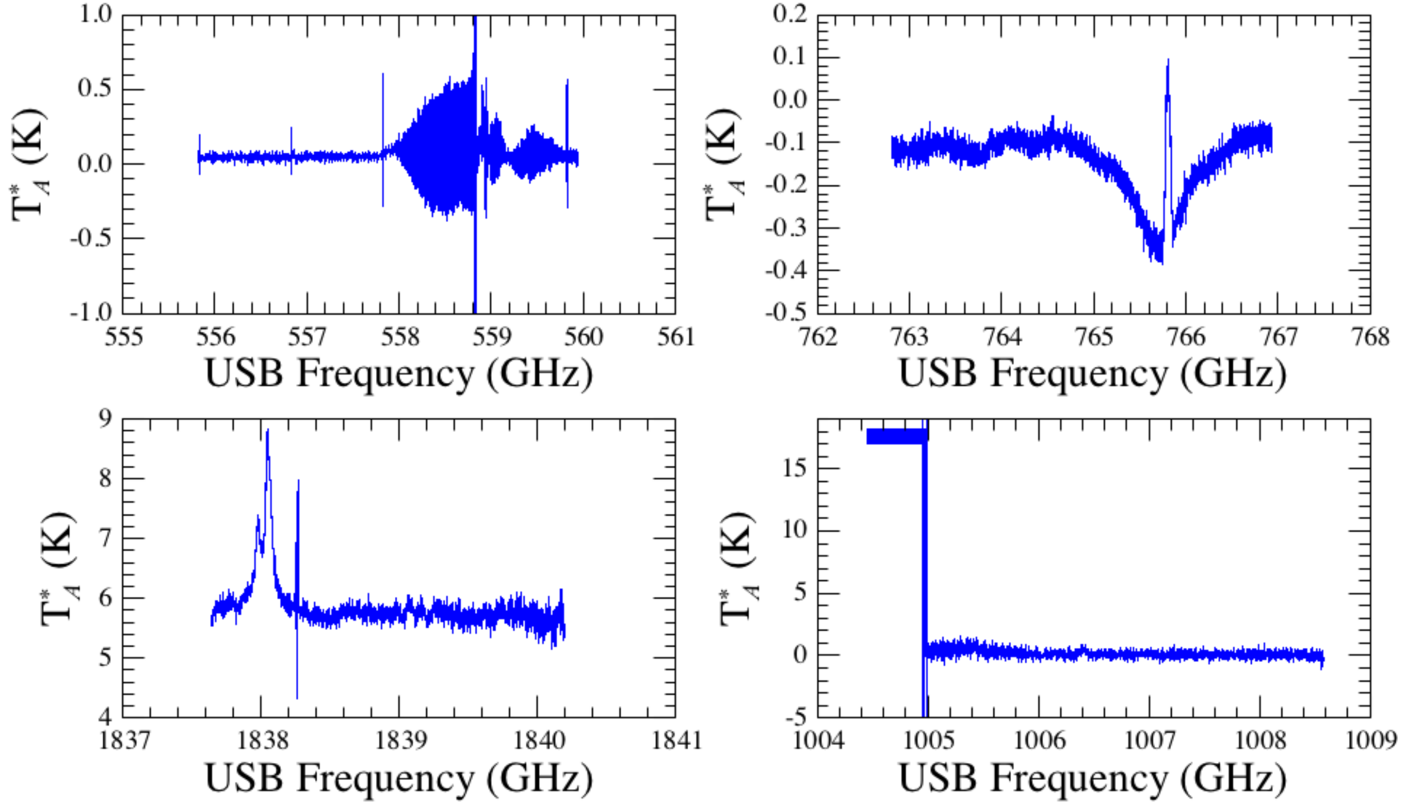
- ***Calibration accuracies***
  - Absolute line calibration uncertainties in the range **2-6%** (on T_A^* scale) plus **5%** due to planet model (for coupling efficiencies)
  - Intensity repeatability better than **~5%** in SIS, **~12%** in HEB bands
  - Continuum calibration accuracy also good but more sensitive to drift
- ***Overall system sensibility is a combination of radiometric noise (T_{SYS}) and drift noise (gain drift, driven by Allan time)***

$$\frac{\sigma_T}{T_{\rm sys}} = K \sqrt{\frac{1}{t\,\delta\nu_b} + \frac{1}{t_A\,\delta\nu_b}\,\frac{1}{\beta}\left(\frac{t}{t_A}\right)^{\beta}}$$

Schieder & Kramer 2001

Lessons learned 1: LO spectral purity (1)

- **Irrespective of the master oscillator lock performance, the LO chain multipliers could enter into oscillation under certain settings, creating spurious responses and signals**
- **Spurious signals** manifested as a variety of strong narrow and broad spurious features (aka *spikes, glitches, humps*, etc), **relatively reproducible from tuning to tuning**



Lessons learned 1: LO spectral purity (2)

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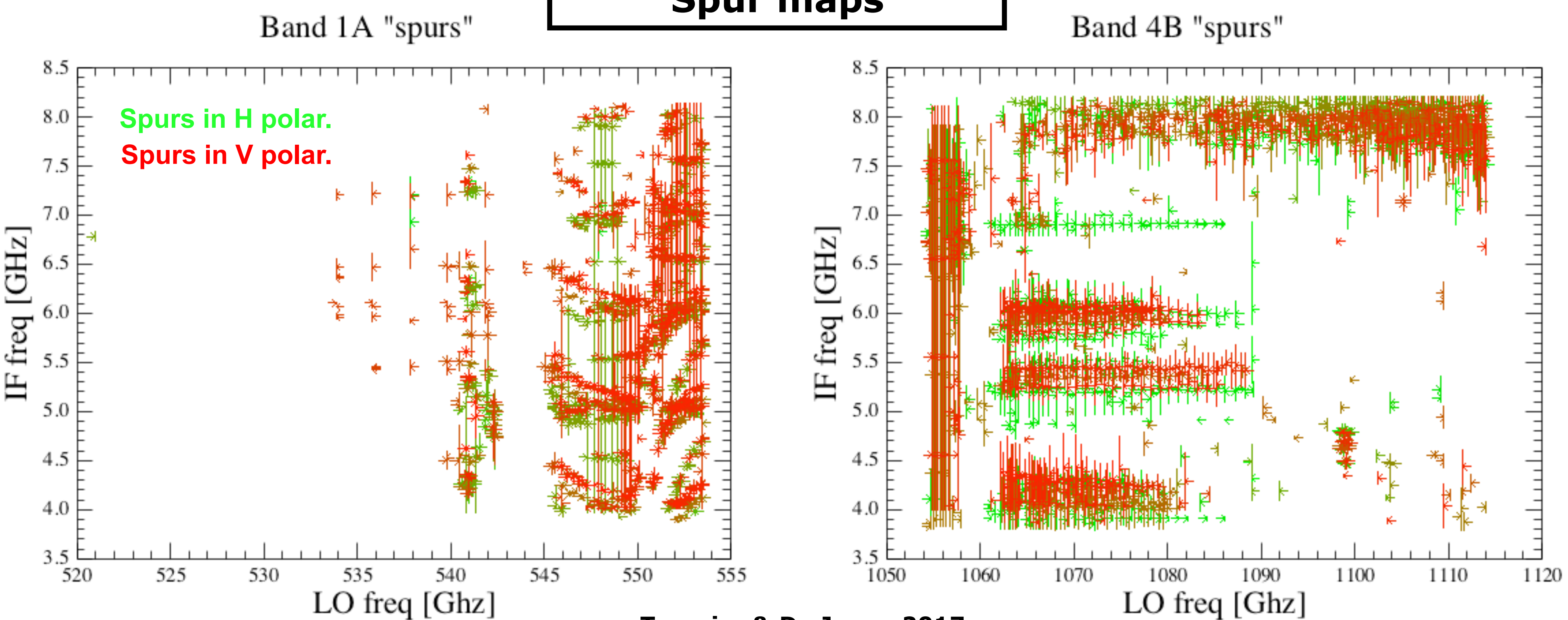
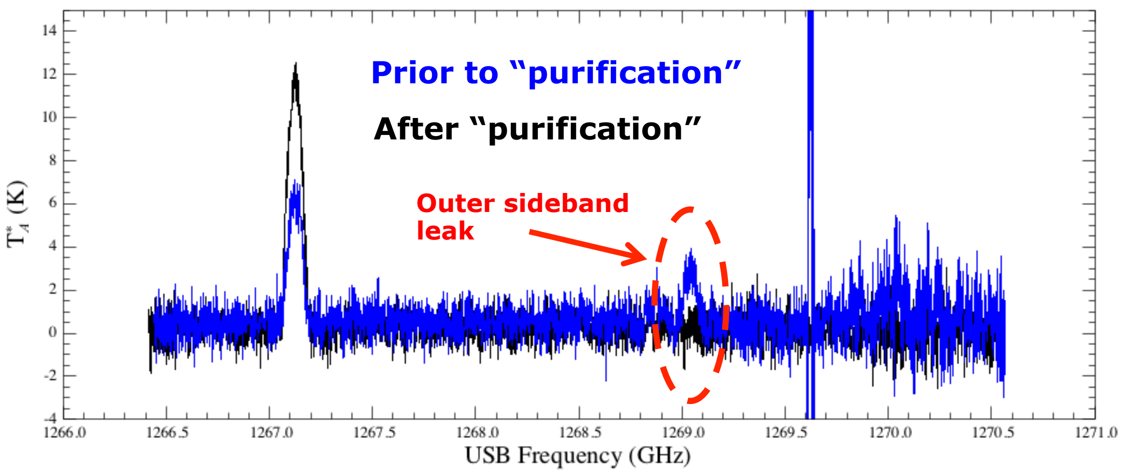
Spur maps



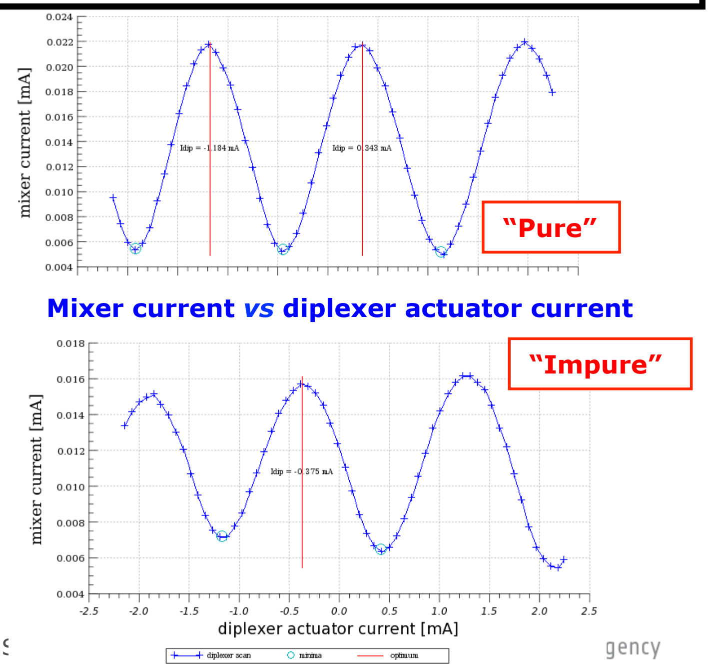
Teyssier & De Jonge 2017

Lessons learned 1: LO spectral purity (3)

- **Spurious responses** manifested as a multi-tone down-conversion system with sensitivity to more than the two expected sidebands ("Outer Sideband" leaks)
  - Implies erroneous line intensity calibration (wrong SBR), together with wrong line identification (ghosts) due to features from other frequency ranges appearing at the wrong sky frequency – usually comes with narrow spurs and excess noise
  - These "**impurities**" were detected pre-launch in bands 3b and 7b, and identified later on in other bands such as 5a, 5b and 7a.
  - Detected through LO multiplier IV curves, together with diplexer sweeps in diplexer bands (low resolution FTS)



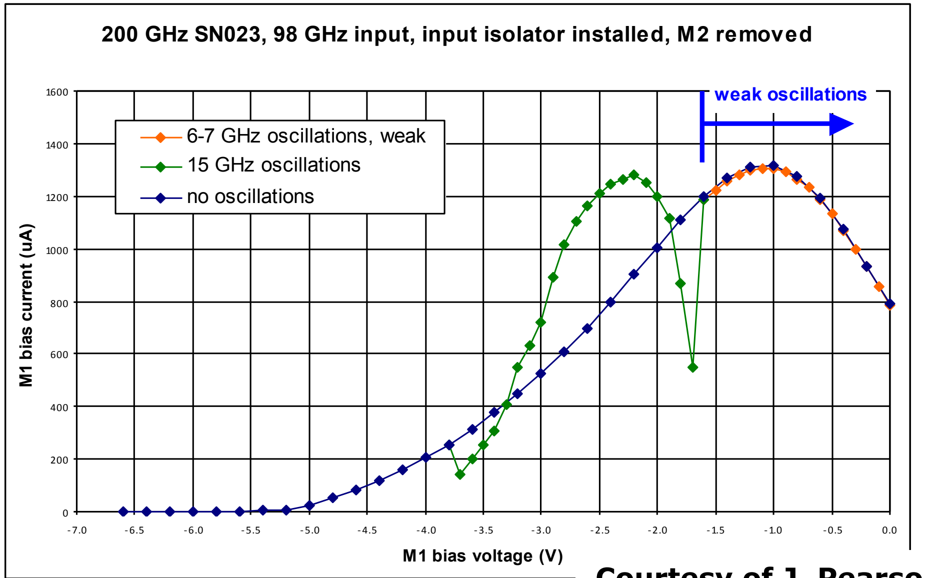
Diplexer scan at 936 (top) and 952 GHz (bottom)

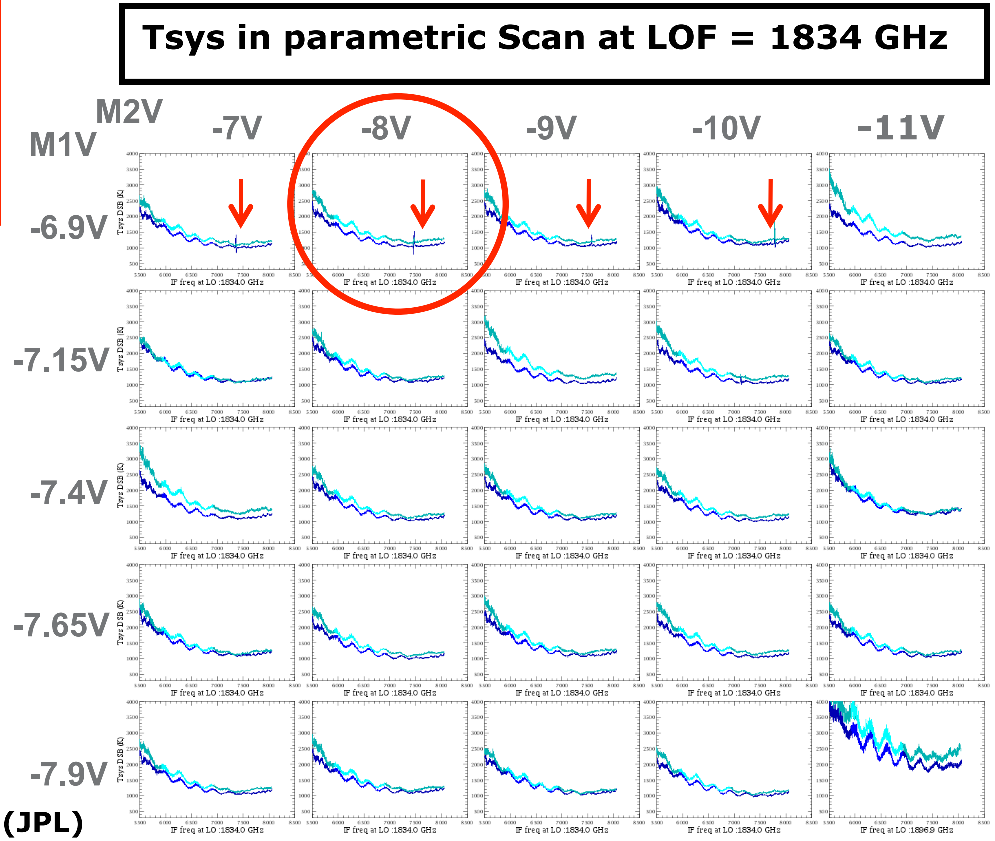


Lessons learned 1: LO spectral purity (4)

- **One big achievement of HIFI was the possibility to purify and suppress spurious signals through LO multiplier setting adjustment while in orbit**
- Approached as parametric scans within allowed range of multiplier biases – best new settings chosen as trade-off between purity, sensitivity and Allan time (some of the latter not always improving when spectral purity recovered)

Key to this exercise was the wealth of telemetry housekeeping collected at high (0.25-1 Hz) rate – monitor your hardware wherever/whenever possible !

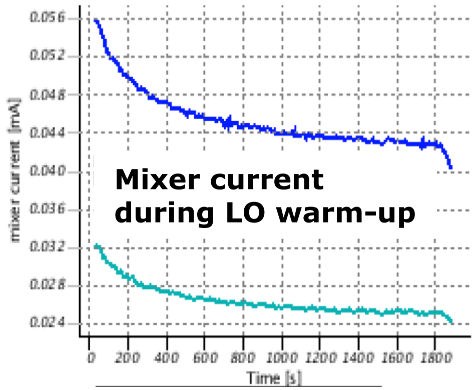




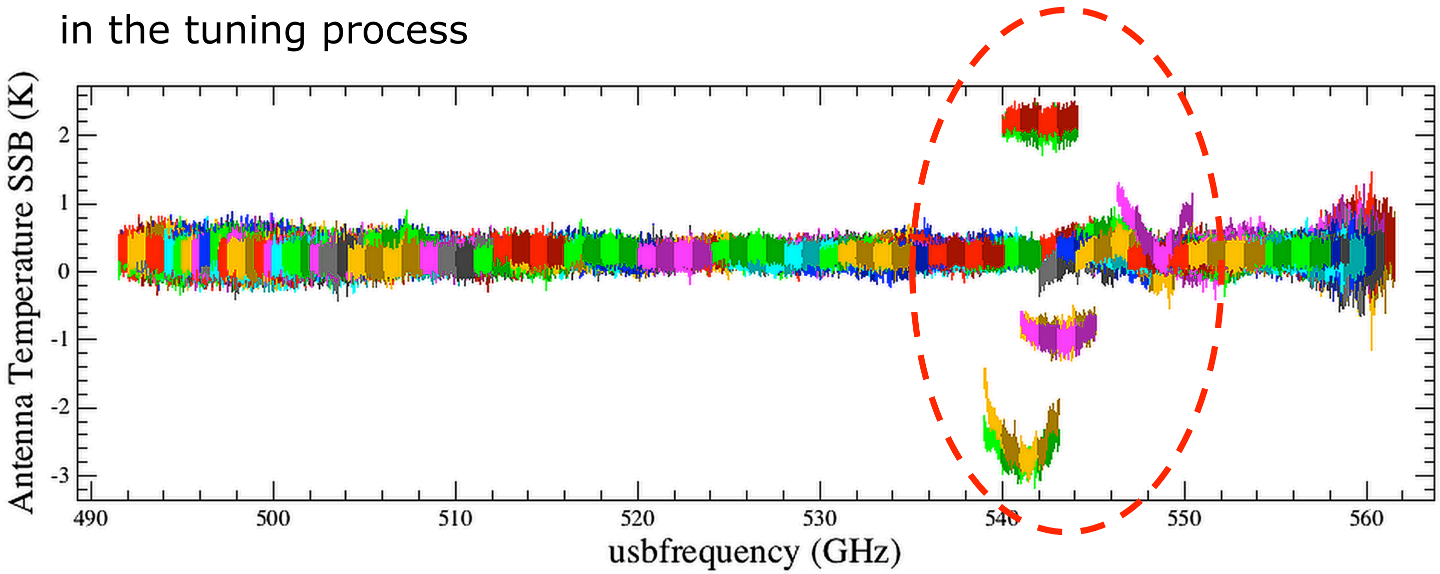
Courtesy of J. Pearson(JPL)

Lessons learned 2: system stability (1)

- **The gain drift of the detectors was driven by the LO output signal stability, which in turn was driven by its thermal stability**
- Main thermalisation effect occurred between LO band changes
  - Warm-up time buffer was budgeted in the observational schedule to let the chain thermalise: between **~5 and 50 min** depending on band and observing mode (worse for HEB and slow referencing scheme – e.g. position switching)

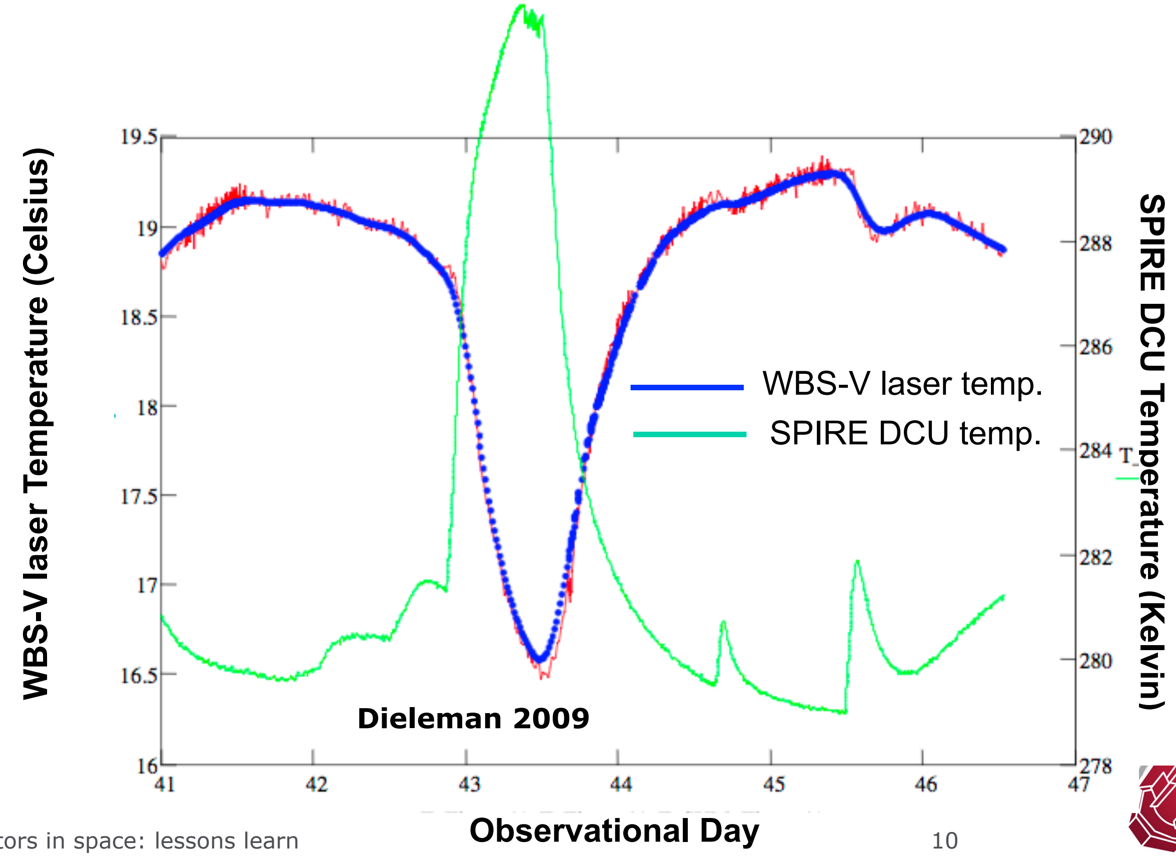


- Within a given band, frequency changes could also lead to thermal settling issues
  - Main affect during spectral scans, although settling dead-times also accounted for in the tuning process



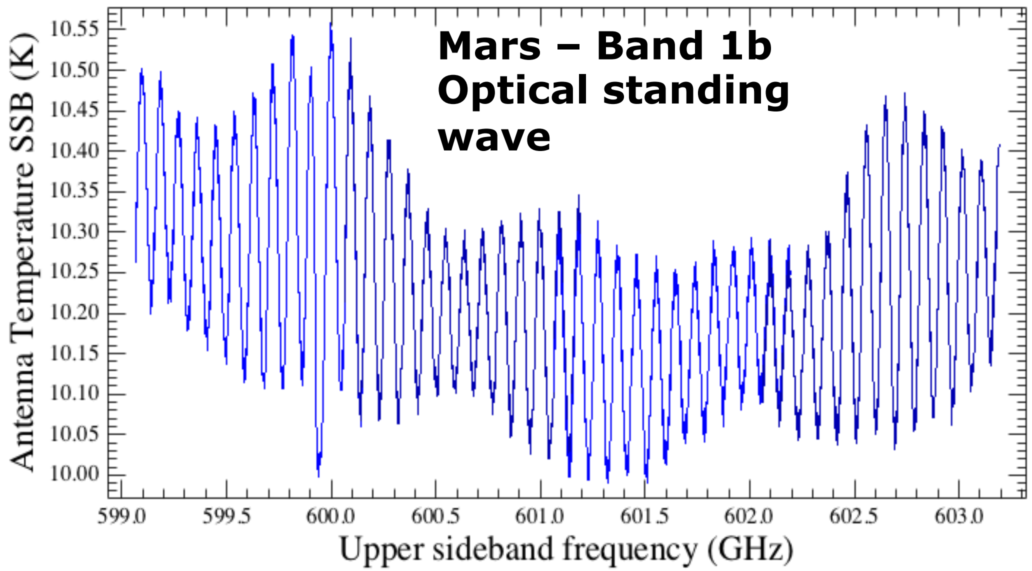
Lessons learned 2: system stability (2)

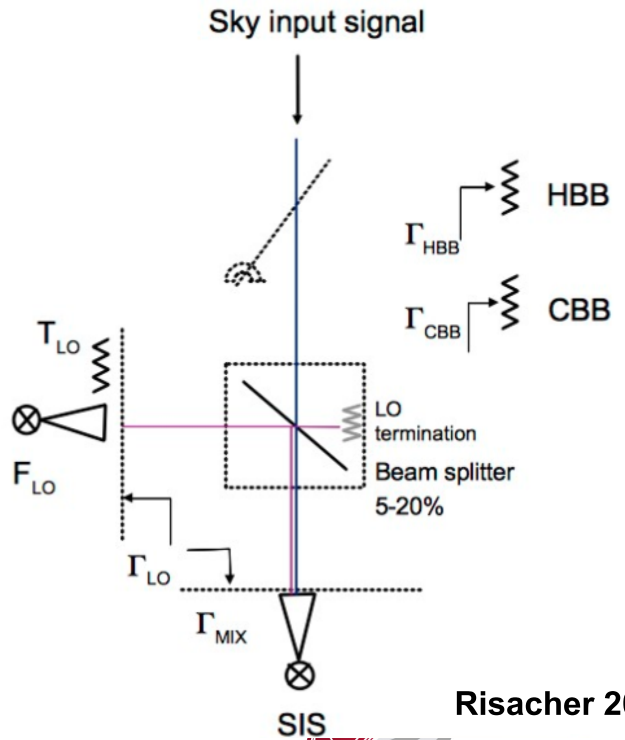
- Although on a different duty cycle, warm electronics did also suffer from thermal affect arising from neighbouring warm electronics (*"l'enfer c'est les autres"*)
  - As an example, operating HIFI immediately after SPIRE implied stability performance of WBS-V out of specif. (origin: inappropriate thermal insulation)
  - Similarly, LOU had to be maintained in dissipative mode to keep WBS-H stable



Lessons learned 3: Standing waves (1)

- **Even after band-pass calibration, some of the HIFI data still exhibit residual ripples, resulting from imperfect cancellation of standing waves present in each total power measurement**
- Most frequent and strongest **optical** standing waves originated from **1) the internal calibration loads (both hot and cold black bodies), 2) the mixer-LO path, 3) the roof-top mirrors of the Martin-Pupplett system – periods between 90 and 700 MHz**





Risacher 2011

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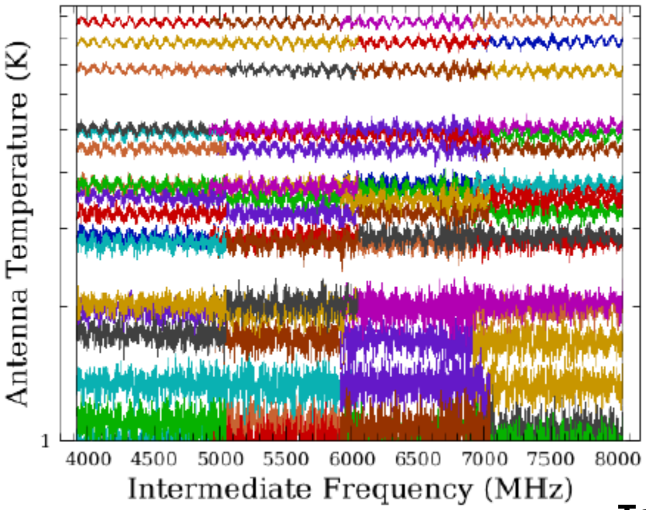
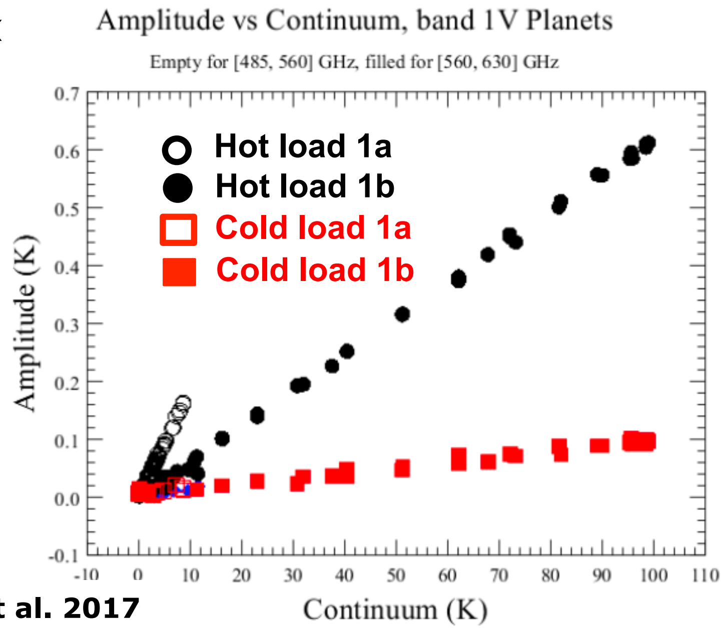
  - Shown to be multiplicative, i.e. affect essentially the gain calibration
  - Implies that flat baselines at zero level do not mean lack of standing wave in the lines, although it all depends on the oscillation phase at a given IF channel
  - Amplitude of the order of 0.5-1% of input flux

Spectra over a Mars raster mapping

(note: log scale)

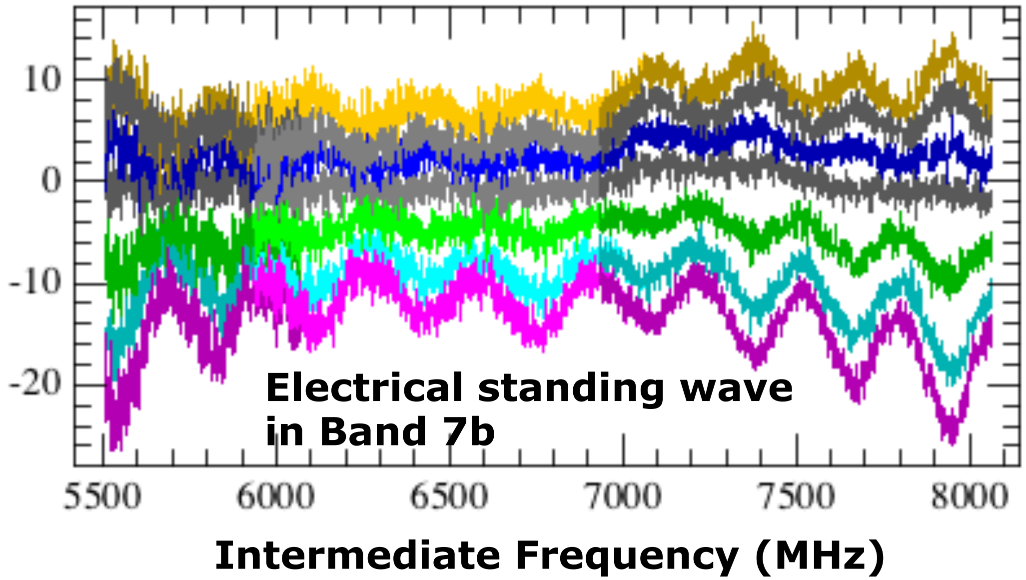


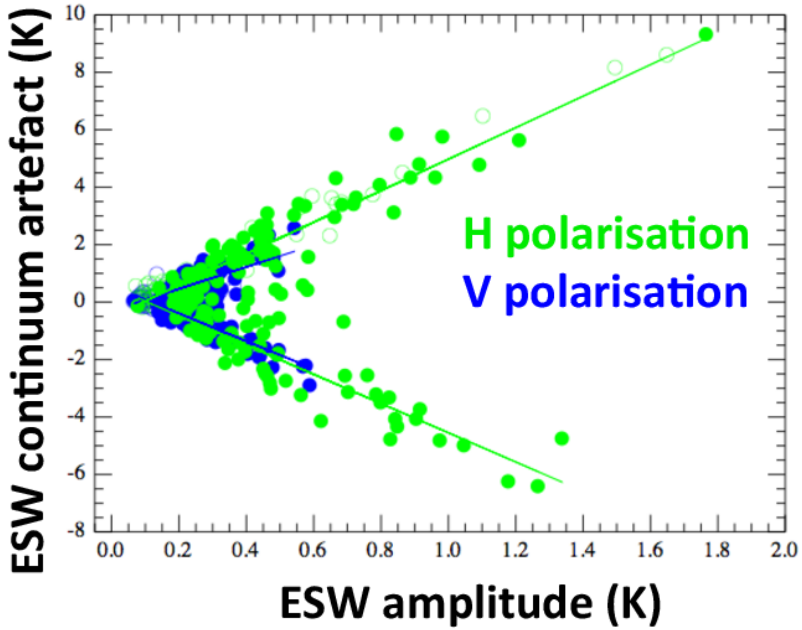


Teyssier et al. 2017

Lessons learned 3: Standing waves (2)

- Another significant standing wave artifact was observed in the HEB bands as an **Electric Standing Wave (ESW) caused by reflection in the coaxial cable between the HEB and the signal amplifier** (e.g. Higgins & Kooi 2009)
  - They exist because of LO output power drift leading to mixer gain variations
  - They are not purely sine in nature
  - Their phase is independent on the LO frequency
  - They introduce a continuum level artifact proportional to the oscillation amplitude





Lessons learned 3: Standing waves (3)

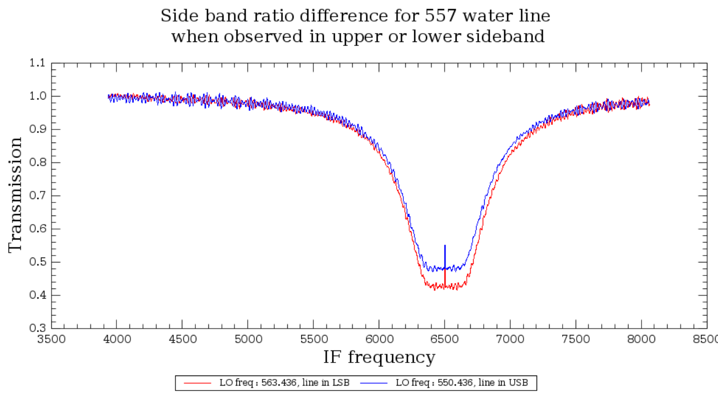
➢ **So, what can we do to avoid or mitigate residual standing waves?**

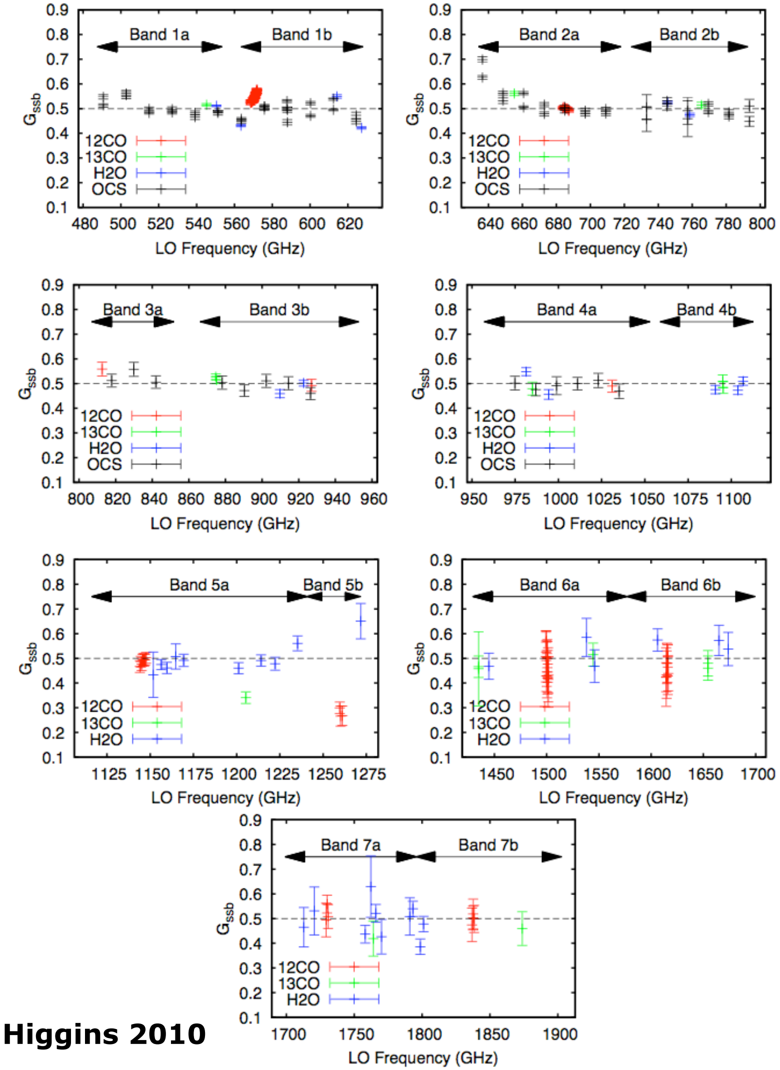
- **Stating the obvious**: Standing waves exist in the calibrated spectra essentially because they don't cancel out in the band-pass calibration.
  - Hardly avoidable when different optical paths involved in calibration and observation scheme, but minimising the **gain drift** will mitigate the impact
- **Optical standing waves:**
  - Coating, and optics non directly orthogonal to chief ray axis, are common sense solutions applied in detector system designs since decades
  - HIFI was no exception to it, yet standing waves exist up to a 1.5% level – *Exception was for mixer-secondary path, resolved via **scatter cone** on M2*
  - Would larger optics/apertures of absorbers help (6w, 8w)?

- **Electrical standing waves**
  - Isolator between coax and first amplifier, at expense of performance
  - Shorter cavity distance will broaden the period, BUT it can make it harder to characterise, esp. when continuum artifact is important to calibrate
  - LO power control loop to avoid mixer gain variation with time
- **Last chance**: correct after the fact – "*defringer*" algorithms in various flavours, + novel technique for HIFI ESW very efficient in that respect (Kester et al. 2014)

Lessons learned 4: Sideband gain ratio (1)

- **The mixer sideband gain ratio of Double-Sideband detectors is a key parameter of the calibration equation, and therefore of the intensity calibration accuracy**
  - Pre-launch assumption was that the SBR would be entirely determined in the lab, based on gas-cell measurements of saturated lines in the HIFI tuning range (*heritage from SWAS*)
  - The reality was that pre-launch measurements just provided the tip of the iceberg, with high accuracy SBR measures at spot frequencies. In some bands (e.g. band 1) this was not enough. For poor stability bands (e.g. HEB) the accuracy was just too bad (ratio assumed to be 1 anyway…)

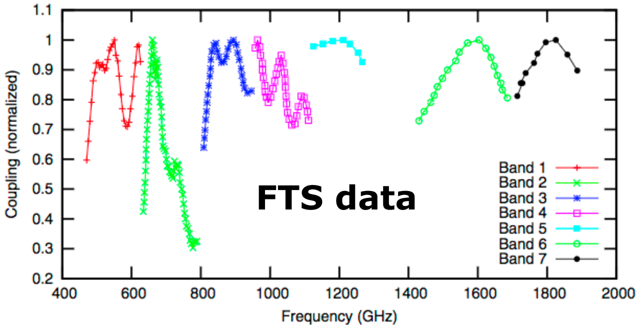




Higgins 2010

Lessons learned 4: Sideband gain ratio (2)

- **In the end the final SBR was only determined 4 years after the end of the mission, using a combination of pre-flight gas-cell measures, and a reverse-engineering of the gains from high signal-to-noise lines in Spectral scans taken in orbit (Kester)**
- **So how could have we done it better?**
  - Ideally, the SBR should come as an element from the EIDP of the mixer manufacturer – often this is impossible due to lack of final LO's, but this is a programmatic aspect
  - FTS measurements of the mixer response are a must, ideally with a pumped mixer (but need LO…)



  - Gas-cell measurements should have been optimised for poor stability bands (faster modulation), and more statistics should have been collected (lack of time)
  - Gas-cell measurements should contemplate non-saturated species, allowing continuous frequency coverage (e.g. methanol), coupled to a dedicated (LTE) modelling of the expected opacities – but molecular spectroscopy parameters sometimes lacking (e.g. pressure broadening coeff., etc)

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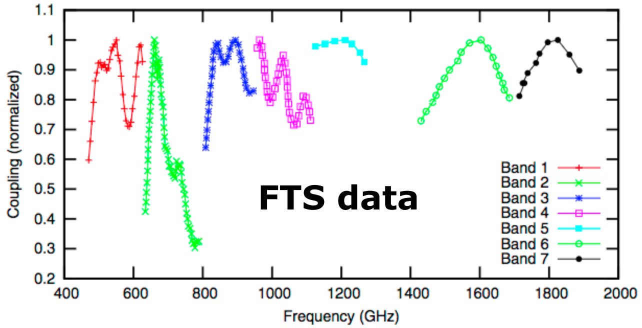

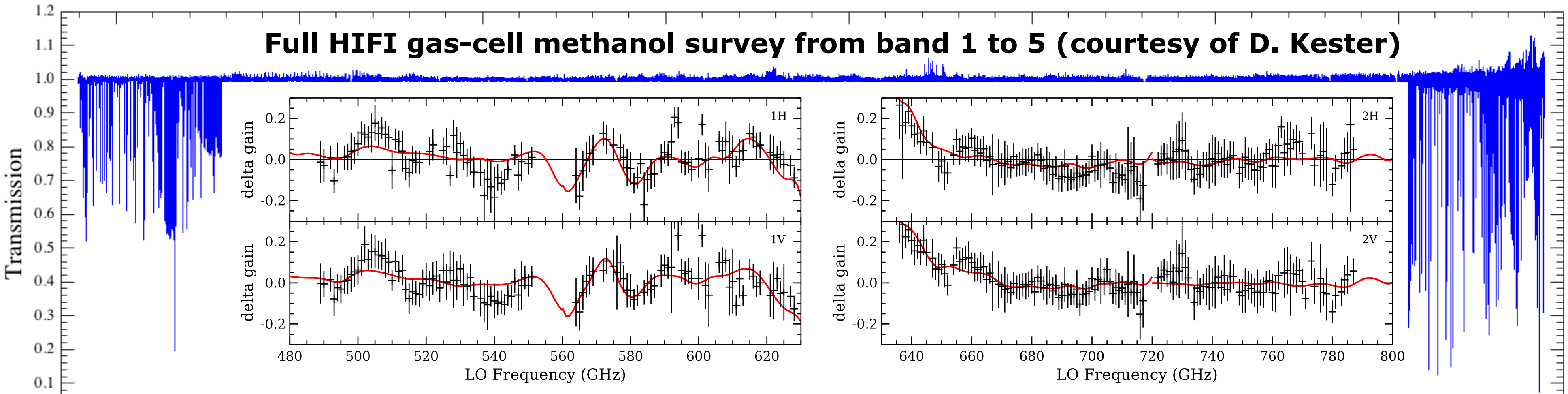

SBR derived from methanol gas-cell data (Higgins), compared to final SBR model by Kester

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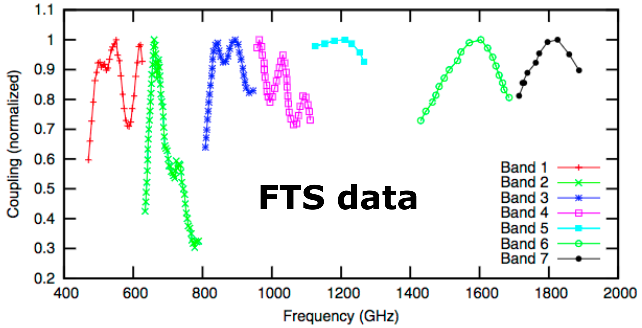
  - Gas-cell measurements should contemplate non-saturated species, allowing continuous frequency coverage (e.g. methanol), coupled to a dedicated LTE modelling of the expected opacities – spectroscopic data sometimes behind (e.g. pressure broadening coeff., etc)
  - **And of course, today, *COULD* actually HIFI be a <u>sideband-separated</u> mixer system?**



Lessons learned 5: Autonomous Operations at L2

- **The instrument configuration setting framework was relatively simple ("small" number of parameters) but with a quite high frequency granularity, and essentially based on Look-up tables (LUT) established both in the lab and in orbit**
  - LO output power tuning based on automatic procedure for optimum operation point assessment and setting, autonomously handled by on-board computer
  - Same for spectrometer IF input power attenuation setting
  - Magnet current tuning only necessary in band 3 and 4 – otherwise static LUT
  - Diplexer tuning and movable optics positions entirely based on LUT
  - Only noticeable revision of settings was in the domain of LO amplifier settings for the purpose of spectral "purification" (plus associated "safeguard" tables)
- **On top of that, the tuning repeatability of the system was extremely good, ensuring reliable time/noise estimates and accurate mission planning**
  - Very few exceptions at spot frequencies, usually related to very narrow sensibility to precise tuning frequency which was variable due to radial velocity change with date (note: no Doppler tracking was necessary)
  - However unpleasant to the end user, even the LO spurious features were relatively reproducible at a given tuning (although moving on the IF on short time scale)

Conclusions

- A couple of more (miscellaneous) lessons
  - ***Frequency Switching*** in HEB bands did not work very well – ***Load chopping*** on the other hand was a very powerful alternative to Double Beam Switching
  - The loss of the HIFI prime instrument through the death of the LSU could be circumvented thanks to a very well thought warm/cold hardware **redundancy philosophy** – versatile on-board SW and HW configuration scheme essential
- (Thermal) stability and spectral purity of the LO output power are key to the end product data quality – operating from L2 is an asset but it is not enough
- Standing waves and sideband ratio ended up being the main contributors to the end-to-end intensity calibration uncertainty
  - About 3/4 of the calibration errors comes from just those two components
- If programmatic allows, address E2E-like assessment of detection chain performance and parameter before full instrument assembly – ILT campaigns are ***always*** too short
- Less related to HW design but essential for instrument understanding: common control and analysis software ("*smooth transition*") throughout ILT until Post-Operation allowed access to telemetry from any phase of the mission – **make sure you have a long-lasting data model from day one, and a long-term data access**