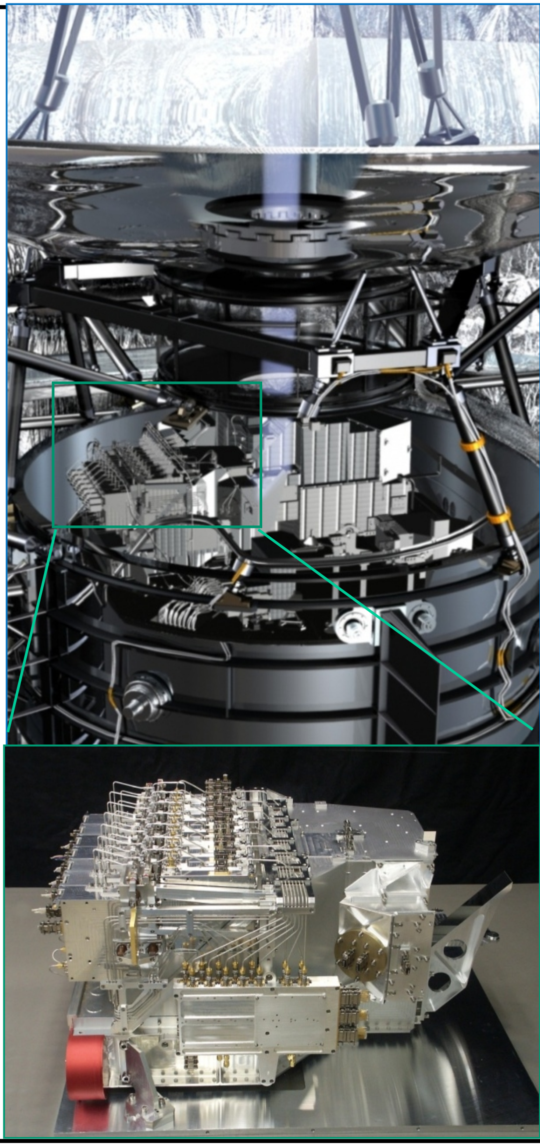


Observing with HIFI

The NHSC HIFI Team

Science support	Application Engineers
Pat Morris	Joan Xie
Steve Lord	Annie Hoac
Colin Borys	
Adwin Boogert	

Thanks - Frank Helmich (HIFI PI)
- The HIFI Consortium

Outline

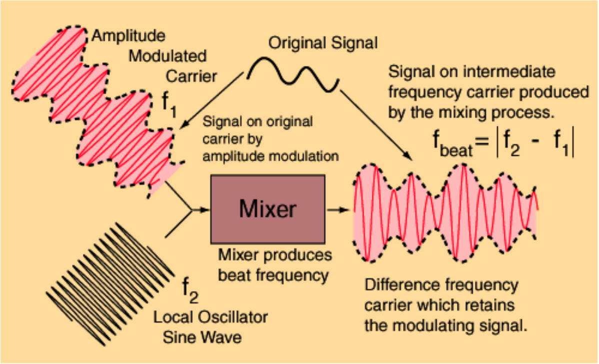
- Instrument
  - How Heterodyne/HIFI observations are done
- Science Highlights
- Instrument performance
  - What was learned about the instrument during PV.
  - How this affects choices of AOT planning
- AOTs and Observation Planning
  - Basic design
  - Calibration schemes: what they are, when to use
  - Overview of the three main observing modes
  - Caveats
- Resources for HIFI users

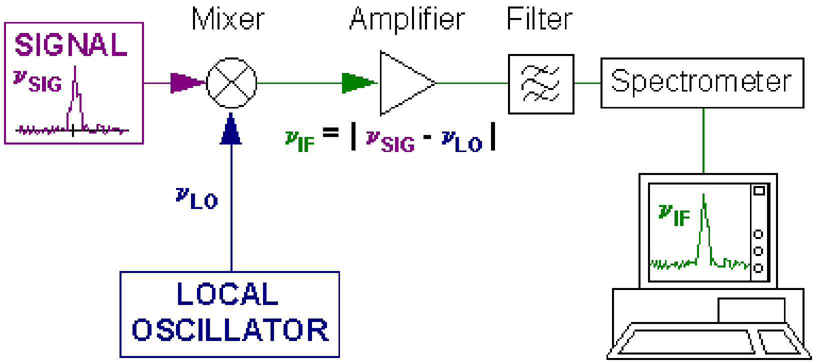
HIFI

The Instrument

The Heterodyne Principle
Mixing Light

- Sky signal is mixed with ultra-stable local oscillator **(LO)** signal such that the difference frequencies **(IF)** can be detected
- IF signal can be electronically amplified and analysed
- Output spectra will contain *overlapping information from sky frequencies above AND below the reference frequency:*
  - **Upper Sideband: LO+IF**
  - **Lower sideband: LO-IF**





HIFI is the most powerful and versatile heterodyne instrument operated in space for observing molecules and atomic lines in the FIR/submm regime at ultra high spectral resolutions.

•Single pixel on the sky

7 dual-polarization mixer bands
- 5 x 2 SIS mixers:

480-1250 GHz, IF 4-8 GHz
- 2 x 2 HEB mixers:

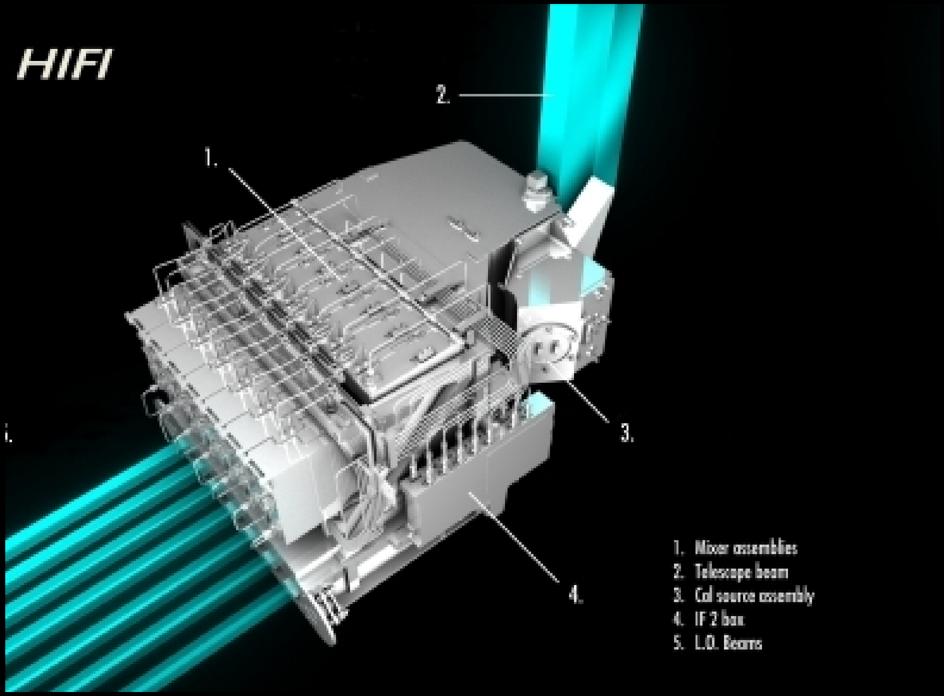
1410-1910 GHz, IF 2.4-4.8 GHz

14 LO sub-bands
LO source unit in common
LO multiplier chains

2 spectrometer systems
-Auto-correlator spectrometer (HRS)
-Acousto-optical spectrometer (WBS)

IF bandwidth/resolution
- 4 GHz (in 2 polarizations)
- 0.14, 0.28, 0.5, and 1 MHz
- Velocity discrimination 0.1-1 km/s ($R>10^6$)

Angular Resolution (w/ telescope):
11".3 (high-ν end) to 40" (low-ν end)



Sensitivity
Near-quantum noise limit sensitivity

Calibration Accuracy
10% radiometric baseline, 3% goal

HIFI AOTs

AOT Schemes with HSPOT 6.0

Reference scheme	AOT I Single Point Observations	AOT II Mapping Observations	AOT III Spectral Scans
1 - Position Switch	**Mode I – 1** Point PositionSwitch	**Mode II – 1** OTF Nyquist or lower sampling option	
2 – Dual Beam Switch	**Mode I – 2** DBS or FastDBS Continuum stabilization option	**Mode II – 2** DBS or FastDBS Raster DBS or Fast DBS Cross Continuum stabilization option Nyquist or lower sampling option	**Mode III – 2** DBS or FastDBS Continuum stabilization option
3 – Frequency Switch	**Mode I – 3** FSwitch Sky reference option	**Mode II – 3** OTF FSwitch Sky reference option Nyquist or lower sampling option	**Mode III – 3** FSwitch Sky reference option
4 – Load Chop	**Mode I – 4** Load Chop Sky reference option	**Mode II – 4** OTF Load Chop Sky reference option Nyquist or lower sampling option	**Mode III – 4** Load Chop Sky reference option

HIFI

Science Highlights

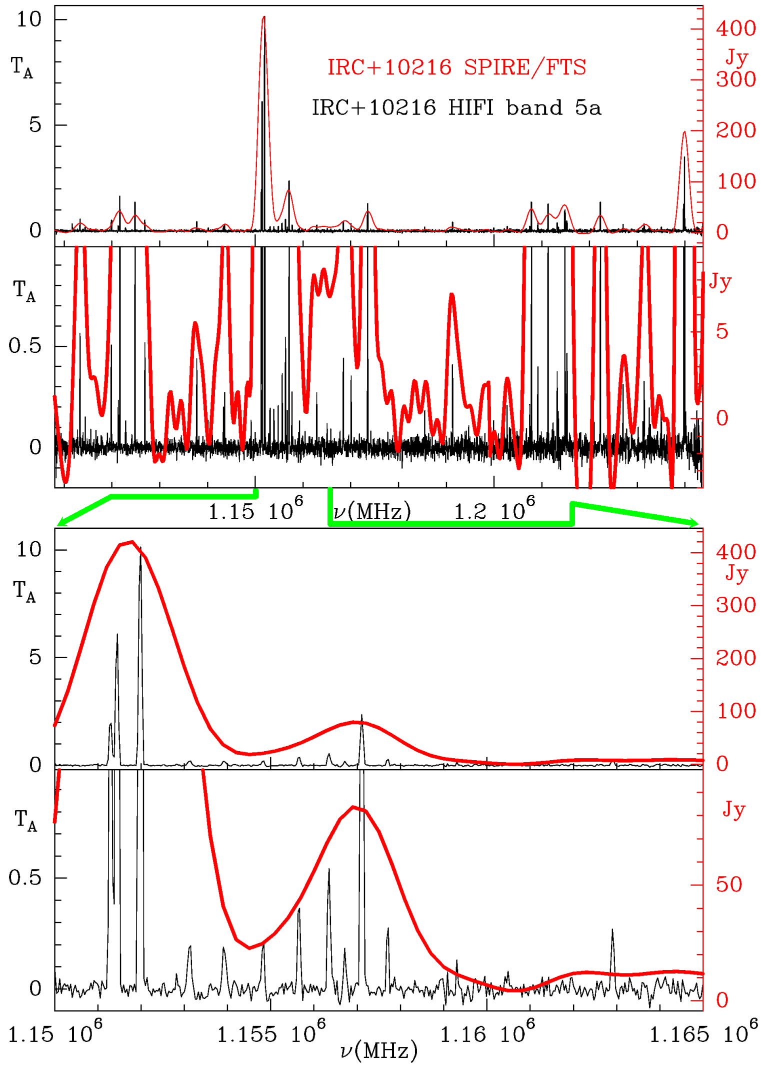
What HIFI is Used For

- HIFI can be used to answer astrophysical questions for which ultra-high spectral resolution is required.
  - Kinematics and dynamics, to 100 m/s
  - Avoiding line blending and confusion
  - Discriminate between emission and absorption

- The bulk of HIFI science involves targets within our galaxy
  - Star-forming clouds
  - Dusty stars
  - Comets

- However HIFI is sensitive enough to study extra-galactic sources
  - Bright IRAS galaxies (low redshift)

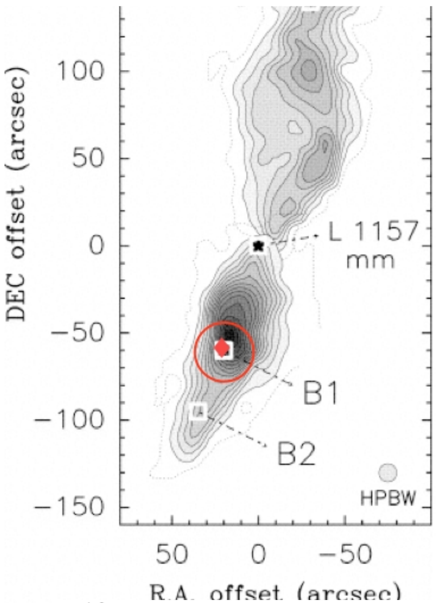
HIFI / SPIRE contrast

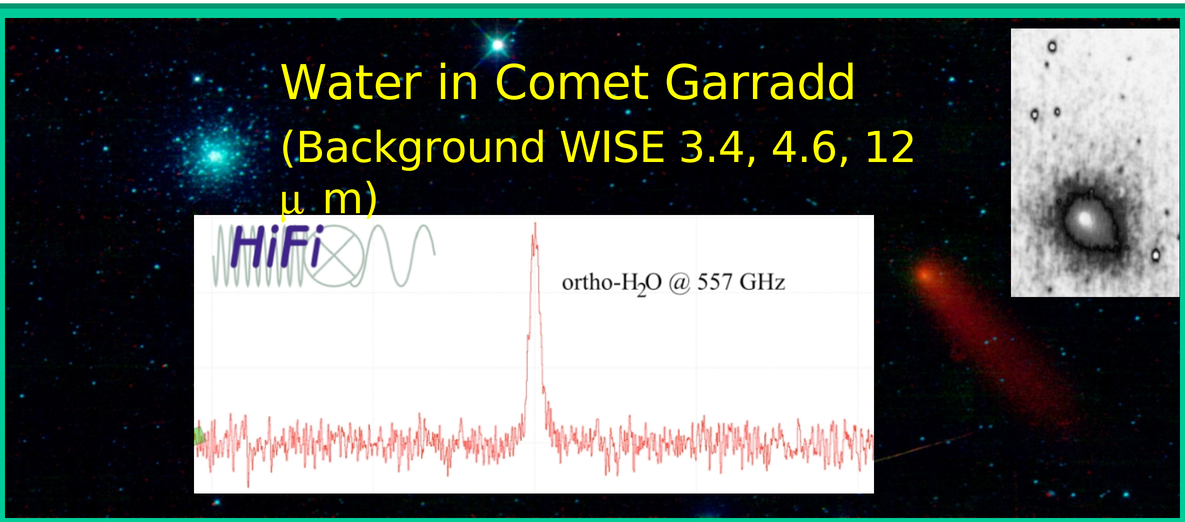


- SPIRE FTS and HIFI Band 5a on IRC+10216 for instrument performance cross-comparison.
- HIFI @ 1 km/s resolution (WBS)
- SPIRE @ ~300-800 km/s

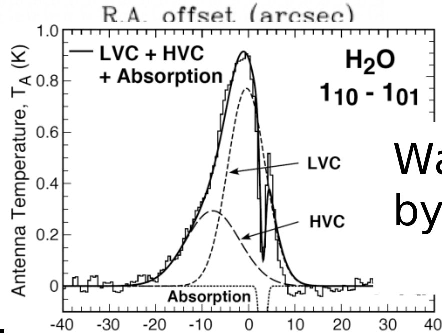
Some Science Highlights

Water and CO from the warm shocked proto-planetary disk OF L1157

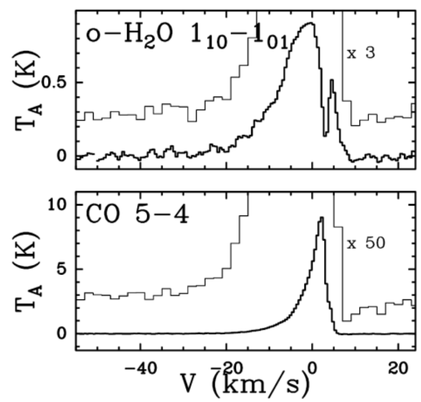


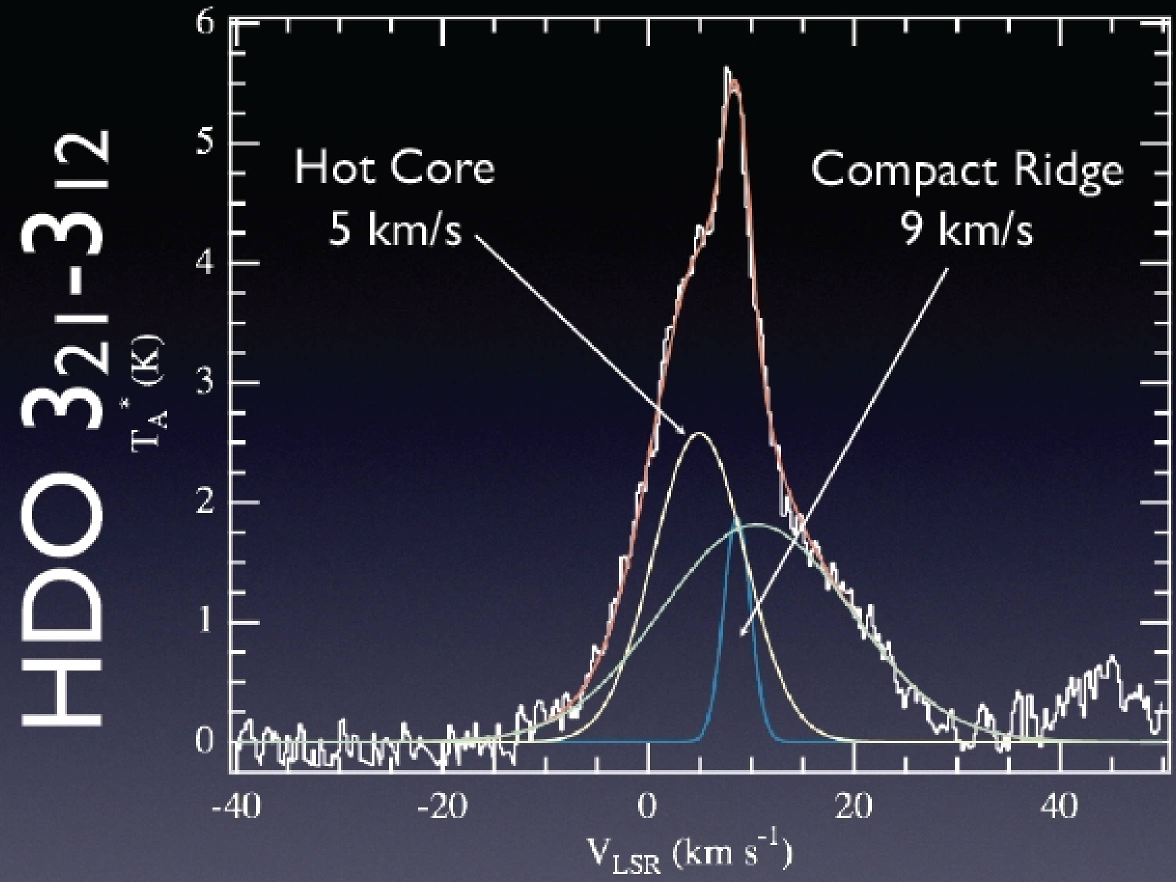


Discovered in Aug 2008, Perihelion: 2009 June 23.10, q = 1.798 AU. First detections of 1_{11}---0_{00} (1113 GHz) and 2_{12}---1_{01} (1670 GHz) rotational transitions in a comet.

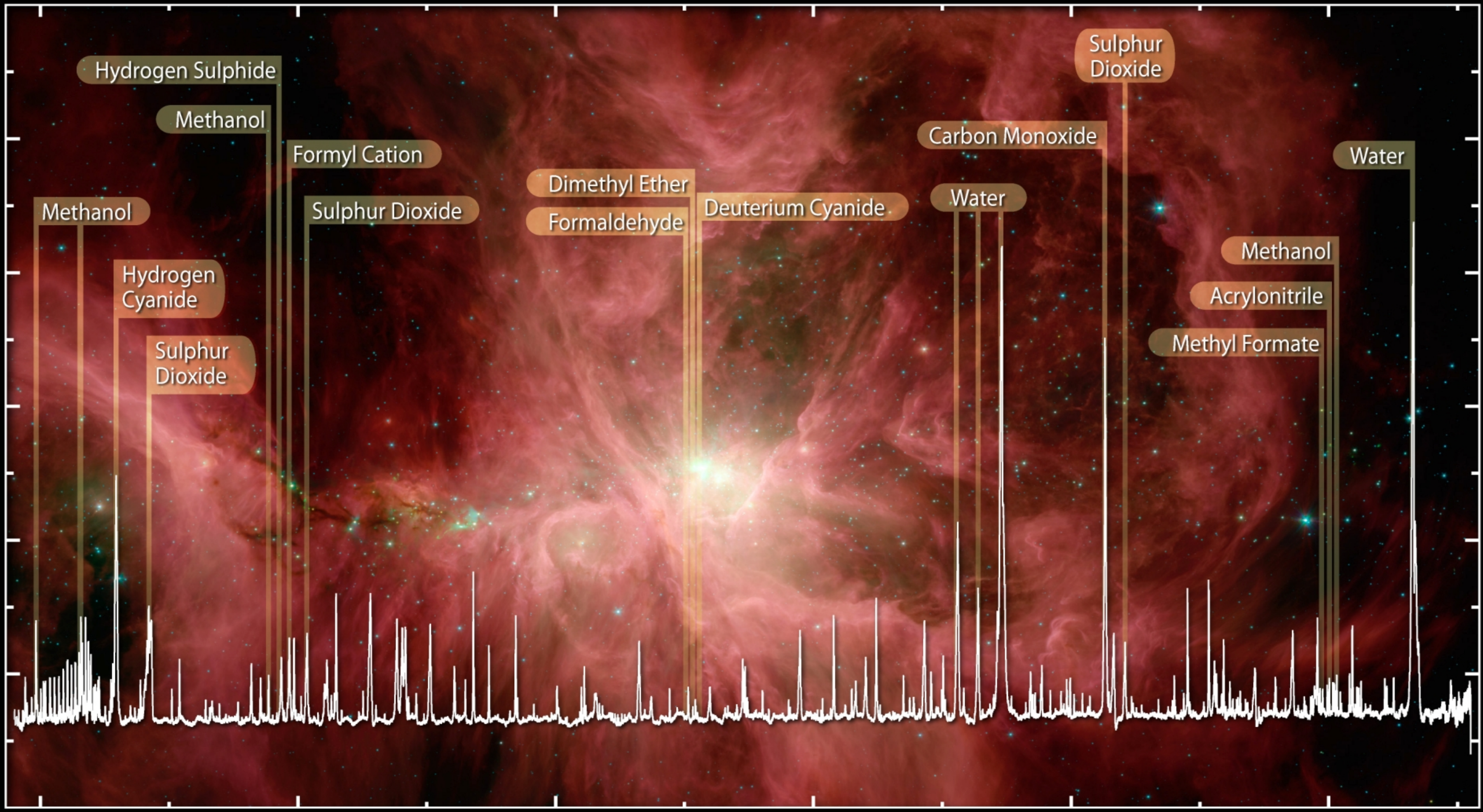


Water absorbed by the gas cloud.





High Spectral Resolution with HIFI



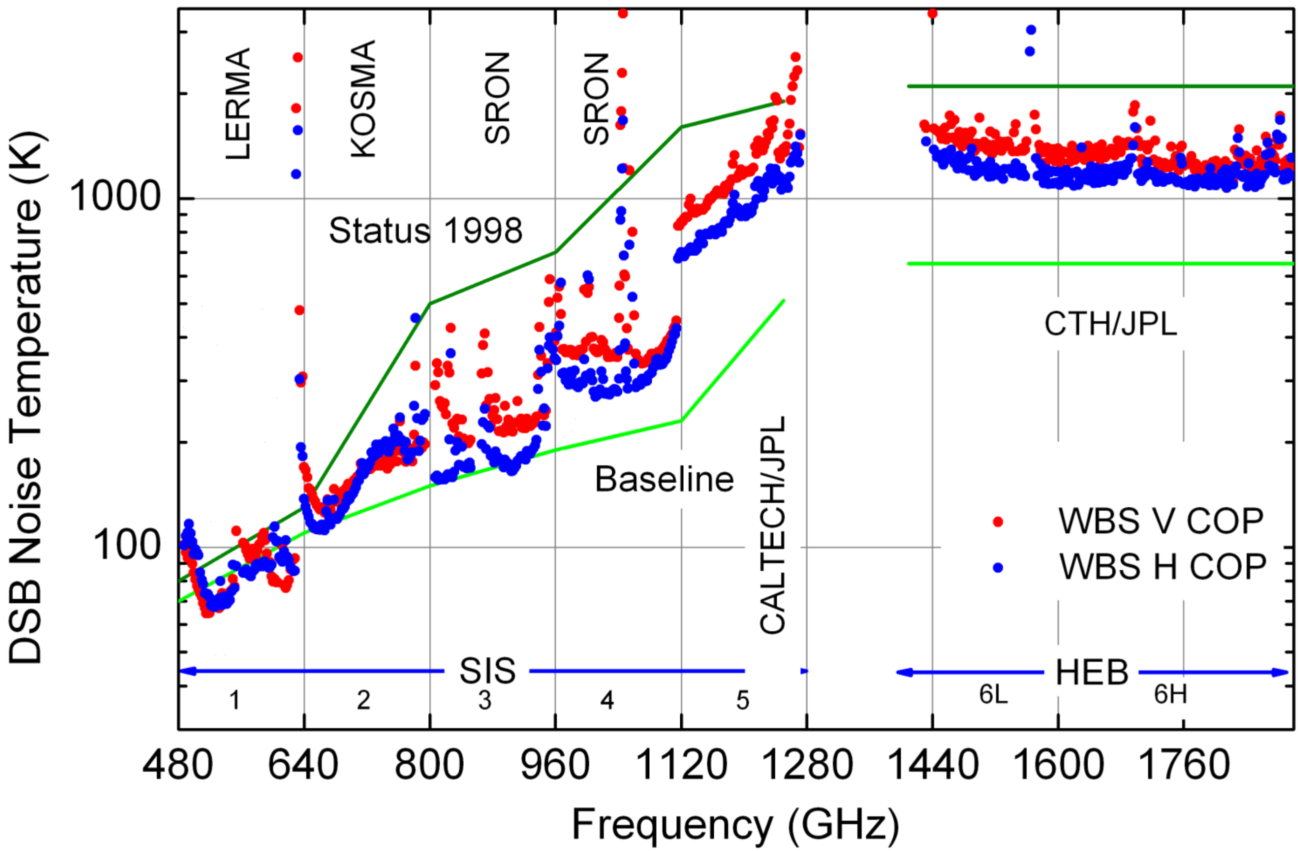
HIFI Spectrum of Water and Organics in the Orion Nebula

HIFI

Instrument Performance

Basic Instrument Performances – Noise Temperatures

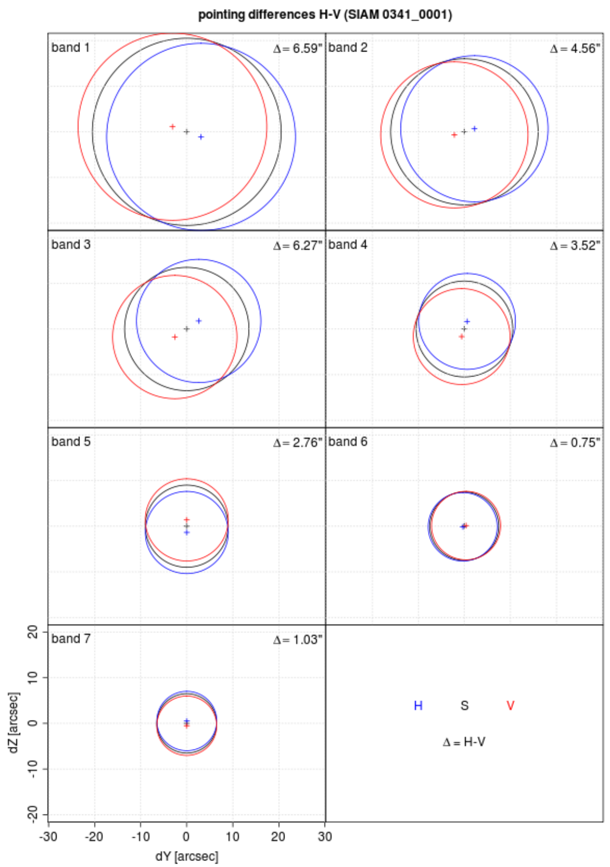
Sensitivities – Tsys/Radiometry



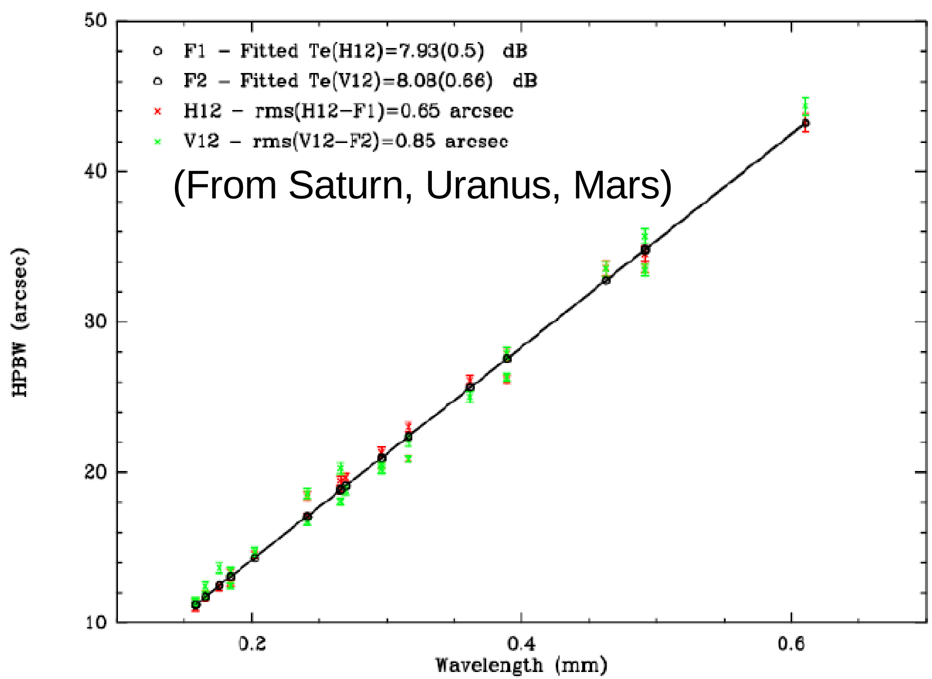
- Sensitivities are driven mainly by System Temperatures and Aperture or Beam Efficiencies.
- No dramatic changes since pre-launch
- One of the main drivers of observing times and calibration loops.
- Noise in flight data generally agree well with HSpot predictions (more later).

H and V Beams on Sky

- HIFI measures H and V polarizations simultaneously.

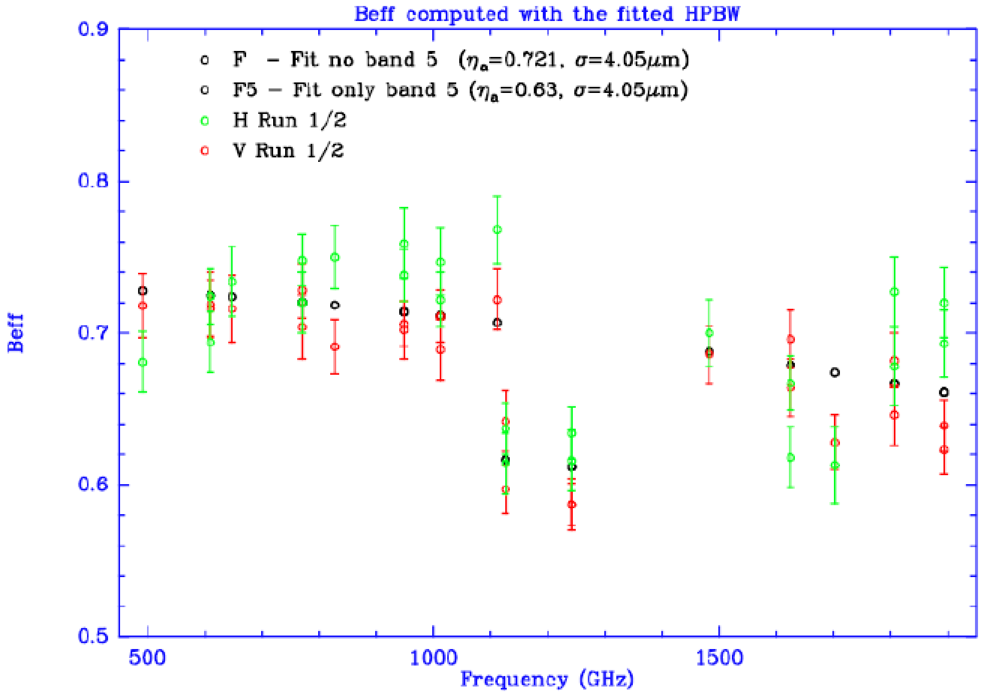


- Pointings are offset sightly on the sky. Offsets are taken into account in the HIFI pipeline since 5.0
- Must be careful about interpretations on polarized sources!



Main Beam Efficiencies

- Beam efficiencies measured on Mars
  - Overall ~10% better than pre-launch estimates
  - Band 5a/b are an exception, ~10% lower.

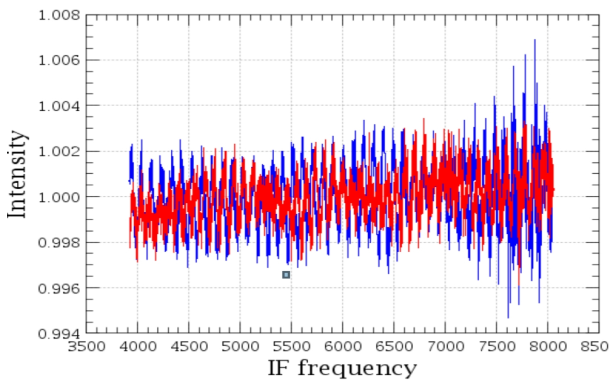


Beff accuracy ± 4 %

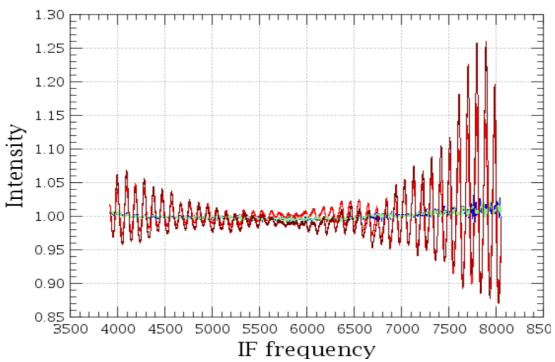
Standing Waves

Standing waves from optical and electronic components seen in HIFI spectra. Pipeline removes those by using appropriate chopping against sky or load, nodding, or frequency switch. Residual waves might still be seen in Level 2 data, and this has been taken into account in HSPOT sensitivity calculations. Much can be taken out in post-pipeline processing. Wave-type is HIFI-band dependent:

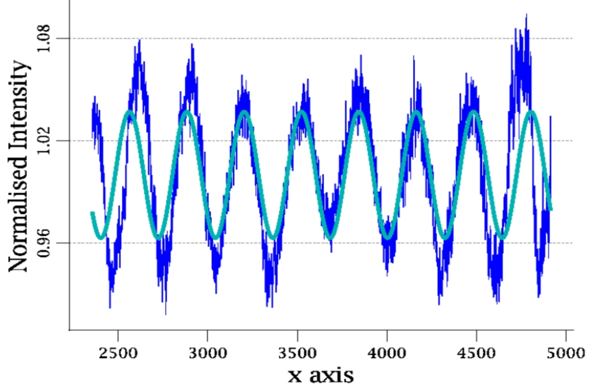
Beamsplitter bands 1, 2, and 5 show sine waves



Diplexer bands 3 and 4 show sine waves with amplitude increasing to IF band edges

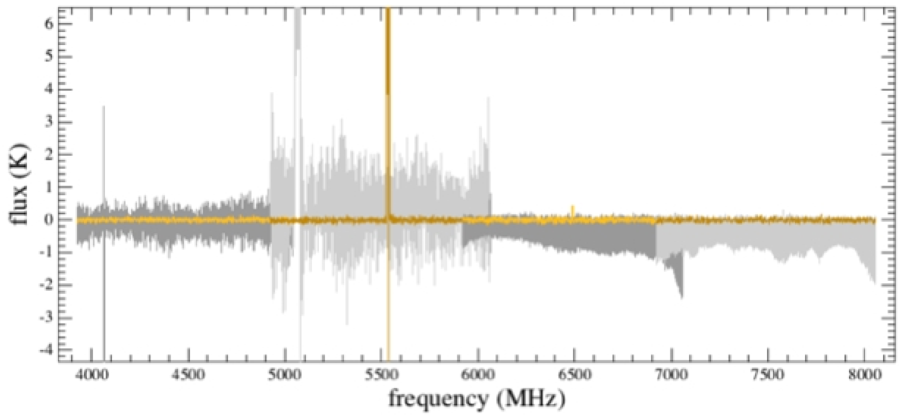


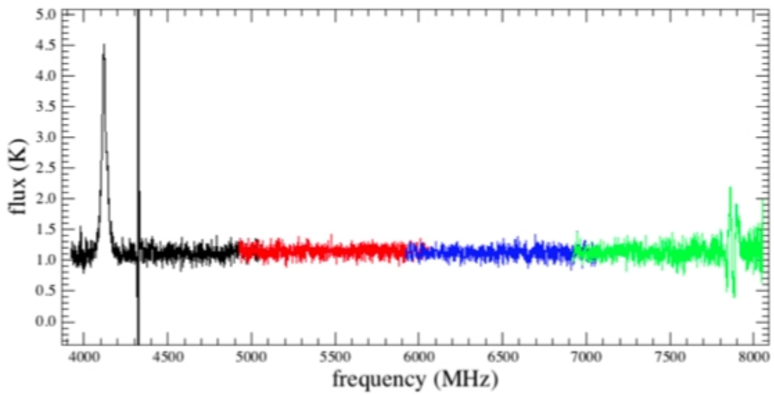
HEB bands 6 and 7 waves are not sine waves. Requires special treatment in pipeline.



Spurious Response in HIFI

- Spurious response in HIFI is manifest as ~25MHz, Gaussian-shaped features in hot, cold, on, and off data.
- **They look a lot like astronomical lines.** To find them, we look exclusively at the load measurements, which are line free.
- Positions of spurs are in general very repeatable.
- Spurs that saturate can often knock out the entire WBS subband in which they reside, or sometimes the ENTIRE DATASET at a given LO tuning.
- Moderate spurs can co-exist with real lines if they are far enough away

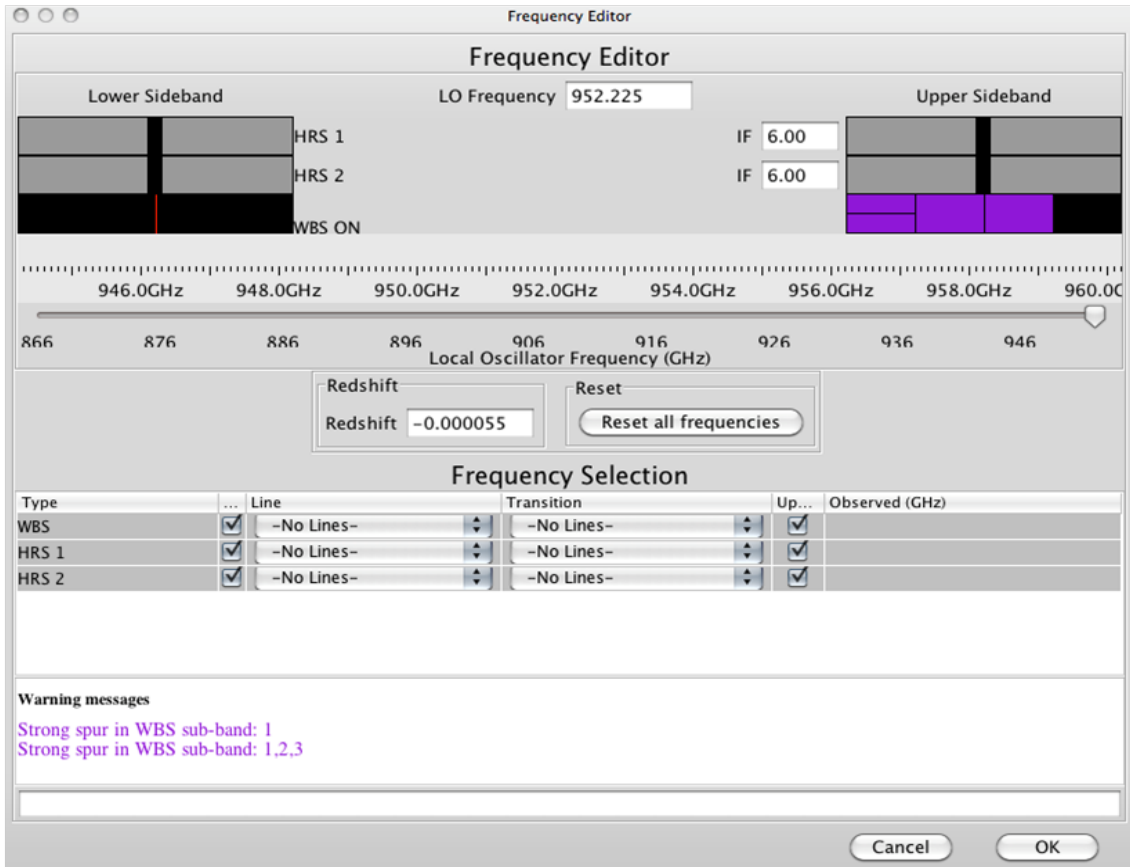




- Many of the most troublesome impurities have been cleaned up by changes to multiplier settings and bias voltages. Example: *in band 1a near 557 GHz H_2O line…band 1A is more sensitive than 1B at this frequency.*

Spurious Response in HIFI

- Avoiding spurs in HSPOT:
  - User should use HSPOT to tweak the tuning such that spurs are avoided
  - It may be difficult in some cases to avoid them, so users are encouraged to contact the help desk for guidance.

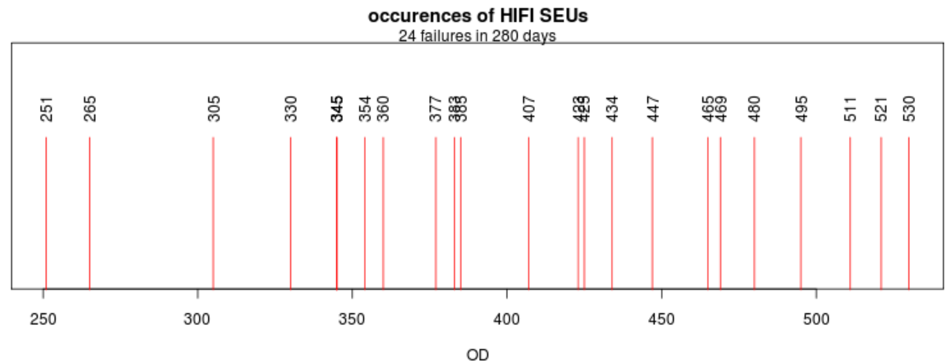


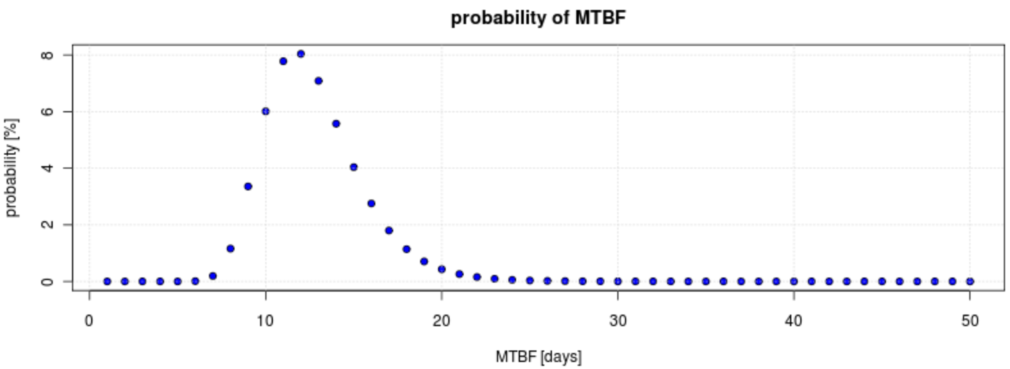
Band 5b purification

- LO-band 5B had several LO spikes at the same time
  - Result is that the IF consists of several frequency bands superposed on each other, resulting in line “ghosts”.
  - Purification efforts took many weeks, a major triumph for modeling of the LO chains!
  - AORs in 5b were released in December 2010.

HIFI Single Event Upsets

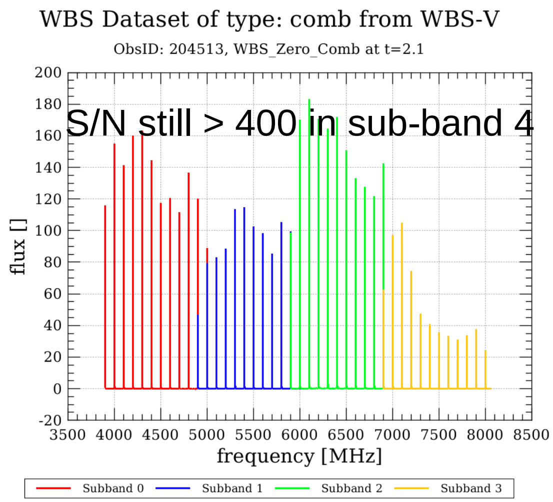
- An SEU in August 2009 attributed to CR on a sensitive memory chip in the LO control unit caused premature power-off of the LOU, killing HIFI's Prime side (DC/DC converter failure)
- HIFI runs on its REDUNDANT side since February 2010, with new intensive fault protection S/W.
- SEU occurring statistically every 12 days
- Recovery now well established and rapid.
- One full power cycle (last resort) has been required, when HIFI stopped reacting to commands.
- ~2 ODs lost to LCU SEUs
- 5 ODs lost to ICU SEUs but PACS rescheduled so no observatory time lost.

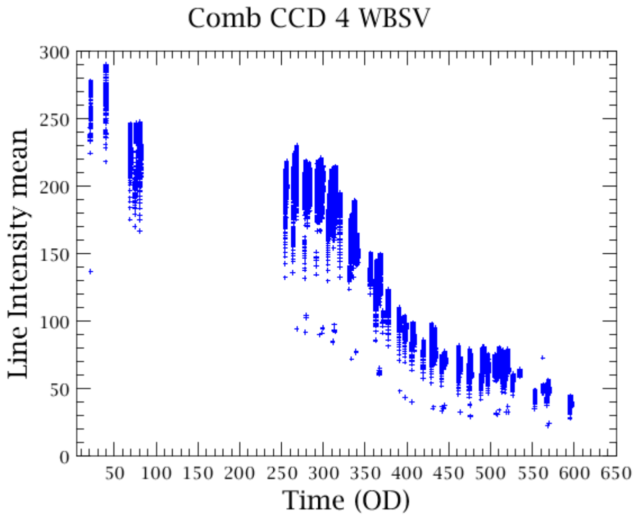




WBS-V comb fade

- WBS-V comb has a failed component, already discovered in 2007. It could not be removed and repaired.
- Comb line intensities continue to drop, now to < 40 counts, much lower than specs.





- Possible reduction of accuracy in determining comb line positions, reduced frequency calibration accuracy expected.
- Alternative method of WBS-V frequency calibration in place, using WBS-HRS cross correlation.
- WBS-H shows no issues.

HIFI

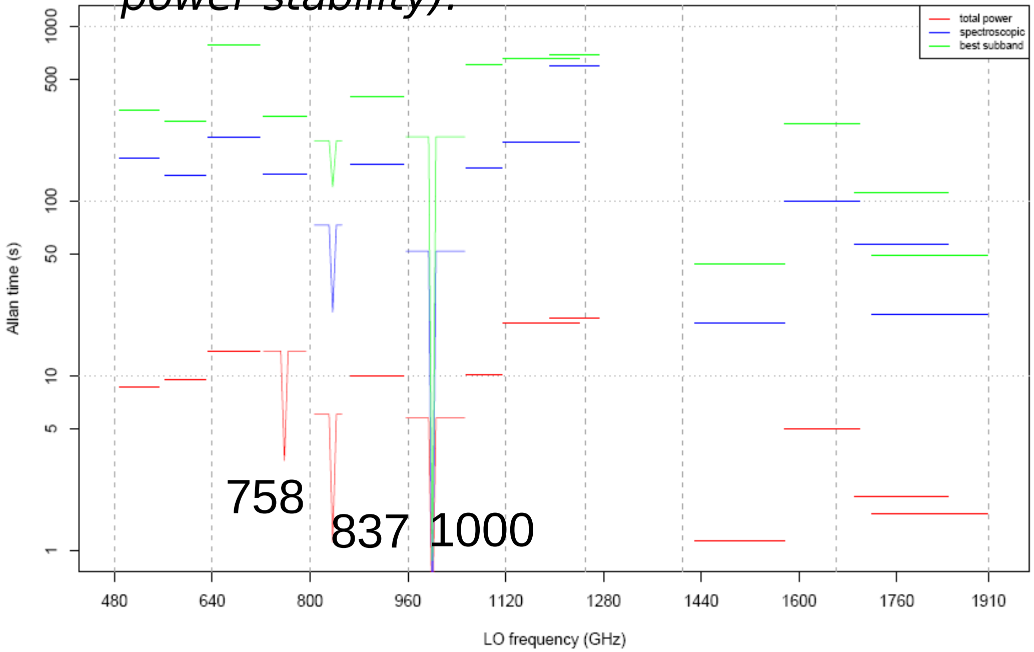
Observation Planning

Part 1: Sensitivity Calculations

- Stability versus Noise
- HSPOT

Observing Efficiency: Stability versus Noise

- Data from Heterodyne instruments like HIFI is affected by instabilities, resulting in drifting baseline zero levels and baseline curvatures (standing waves).
- Drift suppression achieved by differencing schemes: Dual Beam Switch, Position Switch, Frequency Switch, Load Chop (more later).
- HSPOT noise calculations based on Allan times: time at which instrumental drift is comparable to the radiometric noise (T_{sys}) ***over a certain band width at a given resolution,*** *e.g.* at the spectroscopic resolution *(spectroscopic stability)* over all WBS sub-bands or over the best WBS 1 GHz sub-bands or the complete IF *(total power stability).*



- Spectroscopic stability in differencing schemes is generally quite good (>1800 seconds), while this number decreases if the bandwidth increases.
- Different stabilities for different bands, and within bands.
- HSPOT explicitly warns user about very unstable frequencies.

Observing Efficiency: Stability versus Noise

Because the spectroscopic Allan time depends on **resolution and band width**, HSPOT has following parameters to optimize the observations:

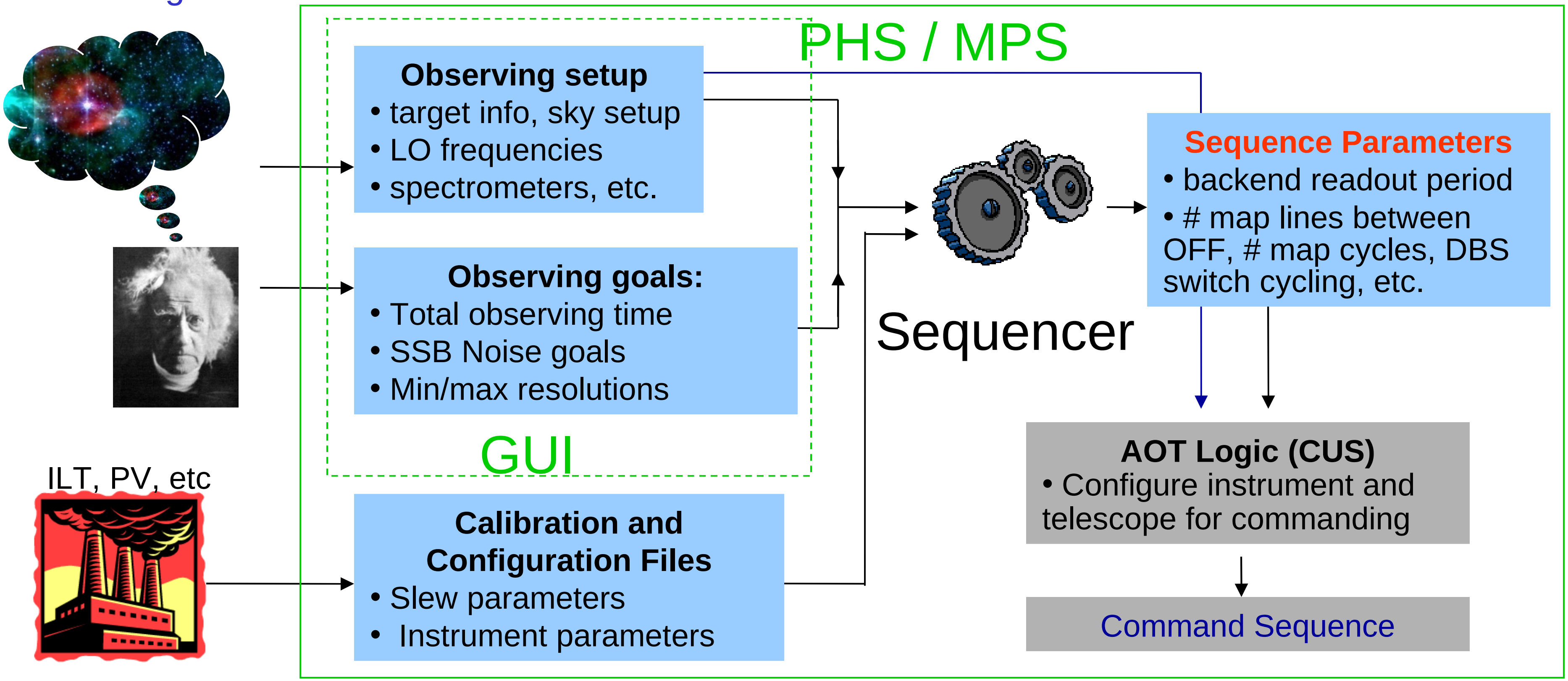
- goal resolution can be entered. This is the resolution at which one intends to analyze the data. Minimum and maximum resolution widths (in MHz or km/s) can be entered. Time estimate is based on maximum width entered. Note minimum width is 1.1 MHz for WBS.
- Check "1 GHz Reference" button for observations of a narrow line
- Uncheck "1 GHz Reference" button for broad lines that cover more than one WBS sub-band.

In addition, if one is interested in the continuum level, use DBS mode and:

- Check "Stability Optimization for Continuum"
- Check "Fast Chop Selected" (recommended for all band 6 and 7 observations even if one is not interested in the continuum level)

The HIFI Sequencer

Sequence parameters determine the length of the observing+calibration loops in the observing modes



Sequence parameters are derived from observation goal parameters via a sequencer program, between the HSPOT interface and the AOT logic.
The sequencer minimizes an observing cost function.

HIFI

Observation Planning

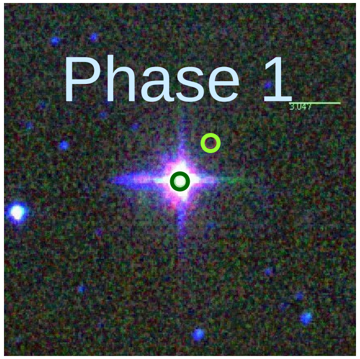
Part 2: Choosing the right reference scheme

- Dual Beam Switch
- Position Switch
- Frequency Switch
- Load Chop

Dual Beam Switch

- Internal mirror chops between ON and OFF positions on sky
- Telescope move (nod) needed to put source in both chop positions to remove impact of standing wave differences in two light paths.

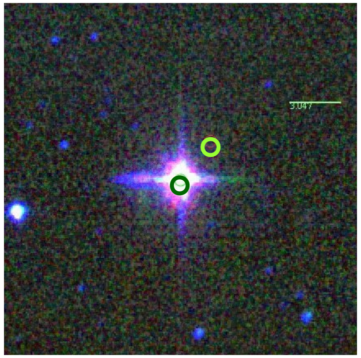
- Very efficient (better than Position Switch)
- Continuum timing of the internal load measurements is optional (for increased stability of the surrounding baseline or continuum, esp. recommended for broad lines).



- Fast chopping is optional, and recommended in Bands 6, 7.
- Caveats:
  - Fixed throw of 3 arcmin: DBS Should not be used when emission is more extended in frequency of interest.
  - Throw orientation constrained by telescope's PA (not adjustable)

Position Switch

- Telescope is pointed alternately to the source (ON) position and a user-defined reference sky (OFF) position



- Distance can be up to 2 degrees: useful for sources with extended emission
- Throw orientation is selectable
- Available with Point and Mapping (OTF) AOTs.
- Can be used in combination with Frequency Switching or Load Chopping (more later).
- Caveat:
  - Less efficient than DBS --- Reference position must be sampled sufficiently frequently to compensate detector drifts.

Frequency Switch

- The LO is adjusted from the “primary” frequency to a small offset, causing slightly different frequency ranges to be observed. Differencing of the two spectra removes baseline fluctuations.
- Very efficient mode.
- Frequency throw is selectable (small, large, positive, negative).
- Mode best suited to spatially complex astronomical environments, where baseline removal cannot be accomplished with DBS.
- Caveats:
  - Lines of interest should be narrower than half the frequency throw
  - Simple spectrum arithmetic may not result in clean baseline removal, and may potentially leave significant ripples in the difference spectrum. Optionally include a Position Switch to an OFF sky position at the same two frequencies (recommended in Bands 3, 4, 6, 7).
  - Not advisable with SScans in Bands 6, 7.
  - Not advisable with OTF Maps in Bands 6, 7, except *possibly* for C^+ at 1890-1897 GHz.

Load Chop

- Internal cold calibration source (10 K) is used as a reference to correct short term changes in instrument behaviour.
- Use on targets where no emission-free regions can be used as reference in either position switch or DBS modes, and where spectral complexity does not allow frequency switching.
- Caveats:
  - The optical path differs between source and internal reference, thus a residual standing wave structure may remain
  - Option to include a Position Switch to an OFF sky position highly recommended (esp. in Bands 3, 4, 6, 7). This has high overhead. [However, total time spent on OFF position depends on the frequency resolution needed to match the baseline ripple, which may be considerably smaller than the integration time spent on the source.]

HIFI

Observation Planning

Part 3: Overview of the different observing modes

- Point Mode
- Spectral Scan
- Mapping Mode

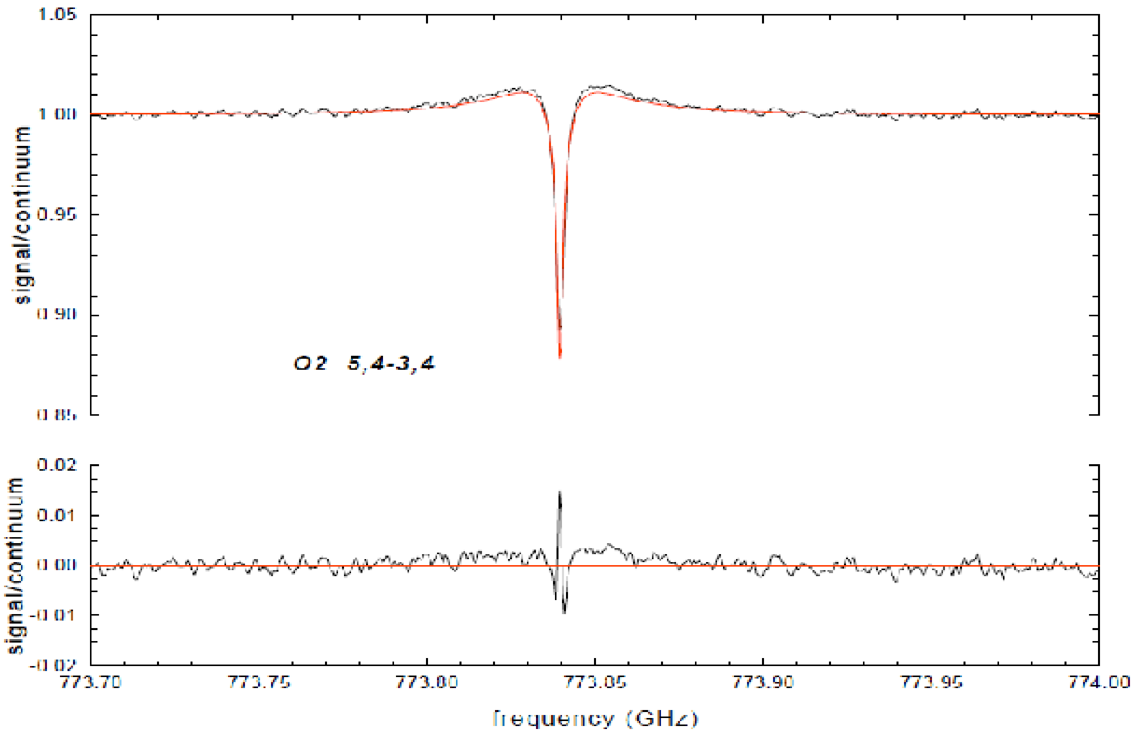
Point Mode AOT

- The point mode AOT is the most basic observation one can do.
  - Operates at a single target position.
  - Operates at a single LO tuning.
  - All reference schemes are allowed.

First submm detection of O2.

Mars fixed frequency, Point Mode AOT, Dual Beam Switching (tracking mode).

Hartogh et al., A&A 521, L49 (2010)



Point Mode AOT

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First subn
detection

Mars fixed
frequency
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521, L49

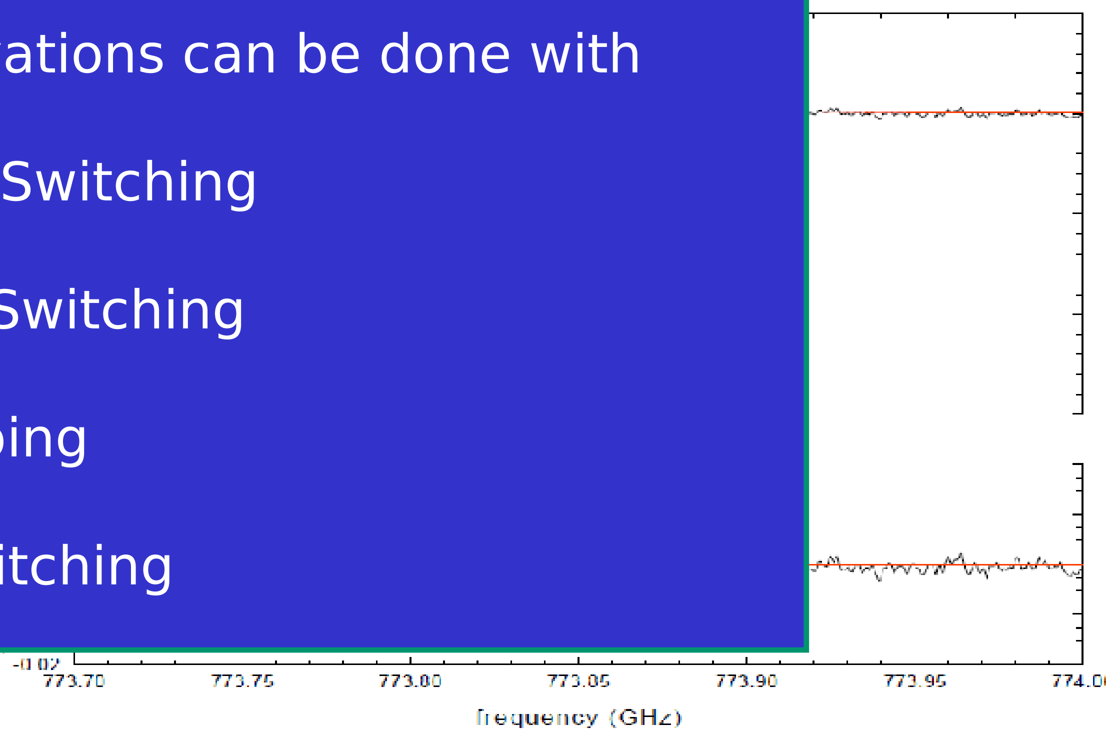
Point observations can be done with

•Dual Beam Switching

•Frequency Switching

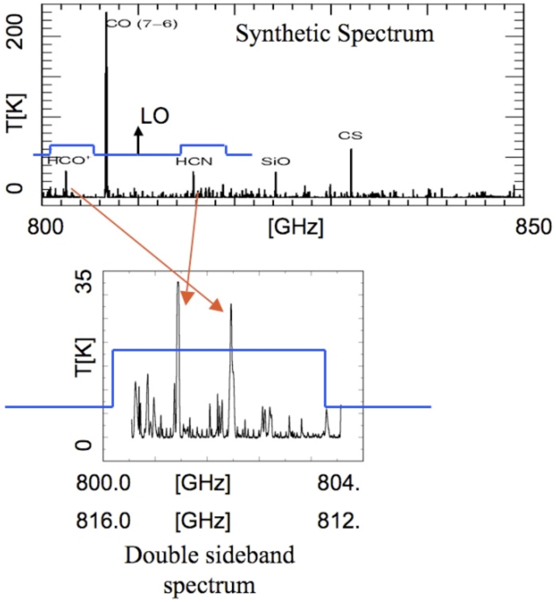
•Load Chopping

•Position Switching



Spectral Scan AOT

- A spectral scan is used when one wants to cover a frequency range greater than the bandwidth of the receiver.
  - Operates at a single target position.
  - Operates at a multiple LO tunings, but limited to just a single band.
  - All reference schemes EXCEPT position switch are allowed.
  - Unlike Point mode, HRS is NOT collected, except in very specific circumstances.
  - Spectral scans are tied to the deconvolution tool
- Deconvolution tries to unwrap DSB data.
  - S(IF)=S(LO+IF) + S(LO-IF)
  - With enough coverage and redundancy, one can iteratively solve for S(nu) using the algorithm of Comito&Schilke (2002).



Spectral Scan AOT

- The user has to choose a redundancy, which is another way of defining the difference in spacing between consecutive LO tunings.
  - Low redundancy (large step size) may hamper the deconvolution algorithm.
  - High redundancy may be too inefficient.
  - Choice should be made based on expected line richness of source
- The user has to choose a spectral range to cover
  - Full bands
  - 'mini-scans' covering < 12 GHz do not tie the LSB from higher LO tunings to the USB at lower LO tunings, but are still popular.
- Caveat for high redundancy.
  - Normally, at each LO tuning, the instrument would collect a spectrum from the loads and the reference. At high redundancy this is very time consuming and instead calibration information is grouped such that observations at one frequency can be used to calibrate observations at nearby frequencies. This may result in standing waves not being fully removed.

Spectral Scan AOT

- The user has to choose a redundancy, which is another way of d … hings.
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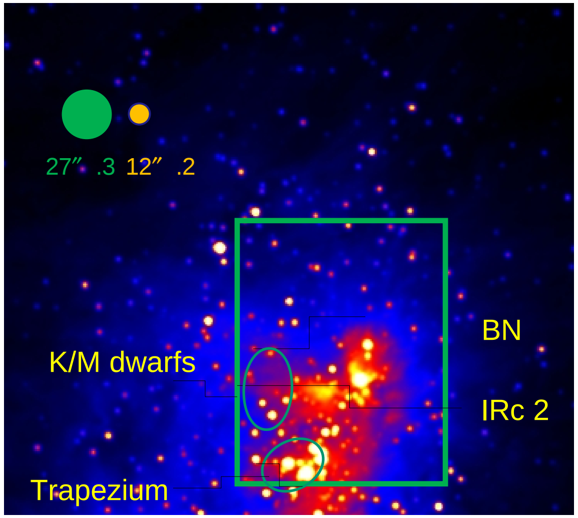
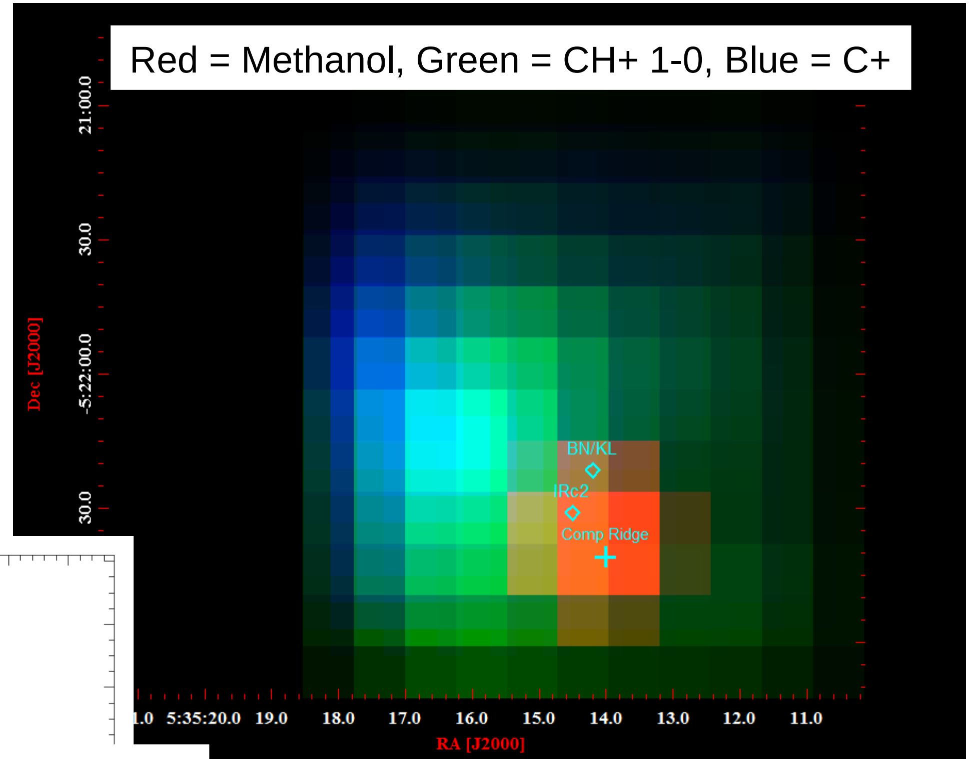
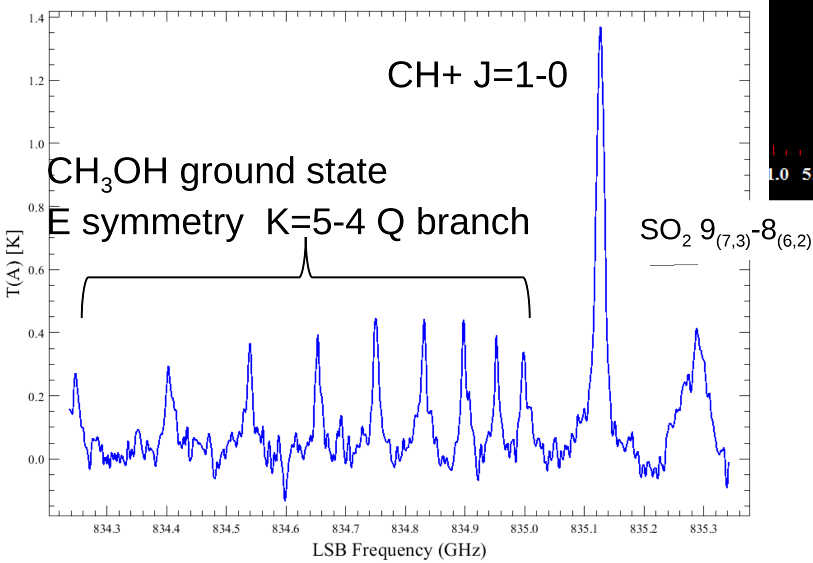
Spectral scans can be done with

- Dual Beam Switching
- Frequency Switching (not bands 6&7)
- Load Chopping

Spectral Mapping AOT
(On-The-Fly mode example)





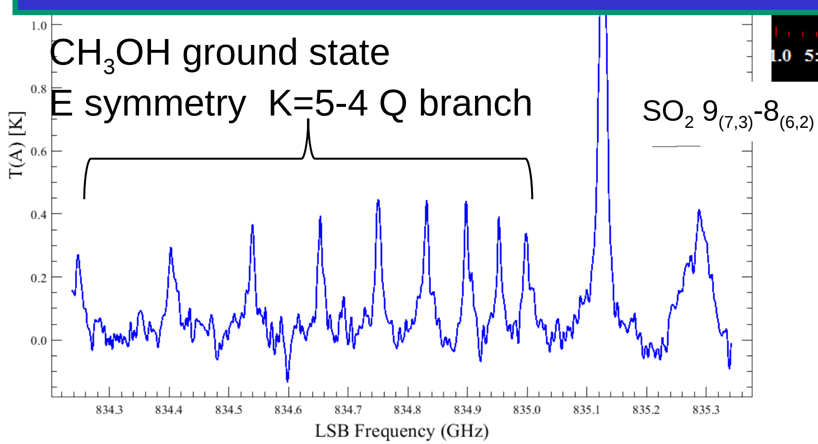


Single LO setting for CH+ and methanol

Morris et al. 2011

Spectral mapping can be done

- **“On the Fly”** (continuous telescope motion and readouts)
  - Frequency and load chop calibration modes available
- **As a Raster**, using Dual Beam Switching
  - Normal or fast chop
  - Calibration timing available for optimum baseline stability.



Single LO setting for CH+ and methanol

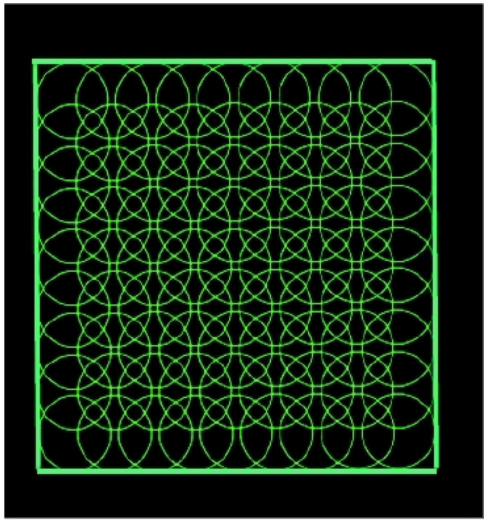
Morris et al. 2011

Spectral Mapping AOT
General Issues

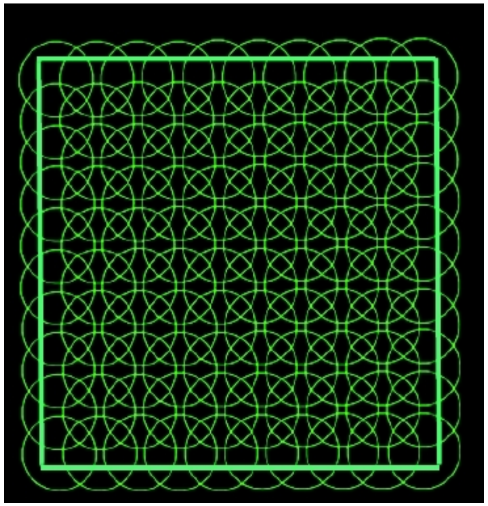
Map coverage:

- HIFI fills requested map area (plot A) different than one may be used to from ground-based telescopes (plot B).
- In OTF mode, HIFI coverage may be in between cases A and B, because mapping is very sensitive to timing correlations between instrument and telescope, and to avoid undersampling, sometimes extra readouts are added.
- HSPOT advice: always plot AOR on image to check actually mapped area

[A]



[B]



Sky sampling definitions:

- Nyquist sampling is not the same as "half-beam" (HPBW/2) sampling.
- Nyquist has ~20% finer grid, requiring ~40% more time for fixed noise goal.

HIFI

Observation Planning

Part 4: Summary

Summary of Caveats on the HIFI Observing Modes

All HIFI Observing Modes released and being scheduled.

- Restrictions:
  - Frequency Switching not offered with Spectral Scans in Bands 6 and 7, LO power is difficult to stabilize between ON and OFF (throw).
  - Frequency Switching not offered with OTF Mapping in Bands 6 and 7, except in the LO range 1890 – 1898 GHz (C^+ frequencies).
- Recommendations:
  - Use fast-chop DBS in Bands 6 and 7, for best baseline corrections.
  - If FastDBS can't be used, LChop is the alternative.
  - Avoid placing key lines of interest at the upper or lower edges of the IF of either sideband, in the bands with employ signal-coupling diplexers:
    - Bands 3, 4: avoid upper/lower 250 MHz.
    - Bands 6, 7: avoid upper/lower 150 MHz.
  - All FSwitch and LChop with all modes should be taken with sky reference, esp in the diplexer Bands 3,4,6,7.
  - OTF Maps may over-compensate for timing correlation and granularities in telescope scannning vs readout rate over requested area. Read time estimate messages, and visualize map for what you want.

HIFI Resources

- HSC and NHSC pages
- HIFI A&A papers (Special Issue)
  - Instrument paper T. de Graauw et al.
  - Performance / Calibration paper Roelfsema et al.
- HIFI Observers Manual
  - http://herschel.esac.esa.int/Docs/HIFI/html/hifi.html
- AOT release notes
  - http://herschel.esac.esa.int/twiki/bin/view/Public/HifiCalibrationWeb
  - Beam efficiency calibrations, and effects in HSPOT and the pipeline.
- Comprehensive lists of links to line lists
  - http://www.gb.nrao.edu/~thunter/terahertzLineList.html
- Calculate expected line strengths using CASSIS:
  - http://cassis.cesr.fr/
- Unit conversion tool (in preparation)
- DP workshops !
  - Always a ton of scripts, tricks, and valuable lore.

HSPOT 6.0.1 vs 6.0.0

Yesterday a slightly modified version of HSPOT was released: version 6.0.1. If you installed v6.0.0, you can use the automatic update feature of HSPOT to get it.

HIFI modifications:

- Retire DBS Cross Map from HIFI Observing Modes
- Take into account sideband ratio changes for band 2A (not yet for other bands). Very little effect, except perhaps low end of band 2A

Non-HIFI modifications:

- Overlay AORs from HROST on HSPOT images (also non-scheduled ones)