HIRDLS

TC	NCA	064

High Resolution Dynamics Limb Sounder

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Subject/Title: **Analysis of Radiometric Jitter Noise**

Contents:

This TC summarizes calculations of jitter noise for several different LOS jitter spectra using a detailed time-dependent radiometric model of HIRDLS (i.e. HIRAM). Particular attention is paid to the out-of-band components of jitter because there is a potential for these components to indirectly find their way into the signal or chopping bands through the nonlinear altitude dependence of the atmospheric radiance profiles.

In addition, a new ITS-level requirement on the allowable LOS elevation angle jitter error, specified in terms of a power spectral density function (PSD), is suggested. The suggested LOS jitter requirement is defined such that when it is combined with pointing error the resulting jitter noise remains equal to or less than the random radiometric error allowed by the IRD requirement of 1 arcsec rms LOS angle knowledge uncertainty. The advantage of specifying the jitter requirement as a PSD function is that it provides a clear statement of the requirement and a clear means for comparing actual LOS jitter measurements against the requirement.

Key Words:

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Introduction

This TC briefly reviews how random uncertainty in the relative tangent height spacing between radiance samples produces an equivalent random radiometric error (referred to as jitter noise), and summarizes calculations of jitter noise for several different LOS jitter spectra using a detailed time-dependent radiometric model of HIRDLS (i.e. HIRAM). LOS jitter is considered to be unmeasured random motion of the LOS, independent of the sources driving this motion. This analysis is not intended to predict the final LOS jitter given vibrational inputs, but simply to defined what level of LOS jitter can be tolerated while still meeting the overall science requirements on accuracy and precision of retrieved geophysical parameters. Particular attention is paid to the out-of-band components of jitter because these components can find their way into the signal or chopping bands through the nonlinear altitude dependence of the atmospheric radiance profiles. The radiance error due to out-of-band jitter components is considerably more difficult to evaluate than pointing or in-band jitter errors because of the nonlinear mixing of frequency components, and requires a detailed model of the signal processing scheme.

In addition, a new ITS-level requirement on the allowable LOS elevation angle jitter error, specified in terms of a power spectral density function (PSD), is suggested. The advantage of specifying the jitter requirement in terms of a PSD is that it provides a clear means for stating the requirement and for comparing actual LOS jitter test results against the requirement. The suggested LOS jitter requirement is defined such that when it is combined with pointing error the resulting radiometric error remains equal to or less than the radiometric error allowed by the IRD requirement of 1 arcsec rms. This should give us confidence that the science requirements on temperature and constituent concentration measurement precision will still be met since the science requirements have been shown to be met for a number of important channels based on the IRD requirement (see for example SCR viewgraphs of retrieval simulations for temperature, ozone and water vapor in the presence of radiometric noise and jitter). HIRAM calculations are made for channels 1-5 and 8, 10-12, and 18 to verify that the jitter noise remains below the IRD requirement given the new specification of jitter. Channels 8, 10-12, and 18 were selected because these channels show the greatest sensitivity to pointing and jitter errors. This is due to the relatively large vertical radiance gradients and/or the low NEN values for these channels. In addition, these channels exhibit the largest second derivatives which is the principal contributor to the out-of-band jitter effect.

This TC addresses only the effects of LOS jitter on the limb radiance measurements. However, pointing errors factor into the overall altitude angle knowledge requirement. There still remains the issue of precisely how well the gyro can measure slowly varying LOS motion and how well corrections can be made to pointing knowledge based on these measurements. This is currently an active area of study by others on the program and it is not addressed here. Nevertheless, it is important to recognize that pointing error and jitter errors do play together to yield a total equivalent radiometric error which must meet the science requirements and therefore, some assumption must be made about the pointing error to allow a reasonable jitter level to be specified. The assumption used in this analysis is that the random pointing error, after all possible calibration and correction factors have been applied, is spectrally flat from 0.1 to 36 Hz with an rms value of 0.7 arcsec over the signal band 0 to 15 Hz.

This is equivalent to approximately 0.5 arcsec rms over the nominal 7.5 Hz global mode bandwidth specified in the IRD.

Pointing and Jitter Errors

The IRD specifies separately, requirements for radiometric noise, given in terms of NEN values for each channel, and jitter-induce radiometric noise specified in terms of random uncertainty in altitude angle knowledge. The IRD requirement on altitude angle knowledge states that the random uncertainty in the relative LOS angle between any two radiance points within a single scan is required to be less than or equal to 1 arcsec (1 sigma) over an effective bandwidth of 7.5 Hz. The altitude angle for a given channel is defined as the angle between the LOS of the centroid of the vertical response of that channel and the X-Y plane of the spacecraft reference coordinate frame (SRCF). This requirement should be interpreted as encompassing uncertainties due to pointing error with frequency components falling below 36 Hz, and unmeasured jitter errors with frequency components above 36 Hz. The 36 Hz cross-over frequency being determined by the effective measurement bandwidth of the gyro, nominally considered to be 0 to 36 Hz.

For altitudes where there is a non-zero slope in the radiance profile, uncertainty in knowledge of the tangent height assigned to a particular radiance sample will result in uncertainty in that radiance value with the error being proportional to the slope of the radiance profile at that tangent height. The sources of relative tangent height errors include encoder readout errors, gyroscope measurement errors, and unmeasured vibrations from the HIRDLS instrument and imported from the spacecraft. The IRD requirement on LOS knowledge was chosen such that the equivalent radiometric error for each channel was roughly equal to the radiometric noise for that channel. This can only be approximately true over the full range of sounding altitudes since the radiometric noise is assumed to be independent of the signal, and therefore constant with altitude, while the jitter noise is strongly dependent on altitude. At some altitudes, the total random radiometric error will be dominated by pointing errors and jitter noise while at other altitudes the radiometric noise will dominate.

The IRD LOS knowledge requirement has previously been separated into pointing error and various jitter components based on frequency, such as synchronous jitter, in-band jitter and out-of-band-jitter[1]. By specifying the allowable LOS jitter in terms of a power spectral density function above 36 Hz, there is no longer a need to make a distinction between jitter components. Nevertheless, it is useful to keep the previous definitions of jitter in mind because it underscores a very important point , and that is that the radiance measurements are especially sensitive to LOS motion at certain well-defined frequency bands while being fairly insensitive to motions occurring at other frequencies. For example, the "pointing band" is defined by the nominal measurement bandwidth of the gyro. However, only the low frequency components of pointing error falling within the signal band, defined by the final lowpass digital filter, lead to errors in limb radiance measurements. Radiance

[1] For a detailed discussion of pointing and jitter definitions, see Venters' TC-OXF-98.

measurements are also very sensitive to unmeasured LOS jitter motion having frequencies falling within the chopper band, defined as twice the lowpass filter bandwidth and centered about the harmonics of the chopping frequency, nominally 500 Hz. These "in-band" jitter components are translated down in frequency to the signal band by the synchronous demodulation process, becoming indistinguishable from pointing error. HIRDLS radiance measurements are fairly insensitive to "out-of-band" (OOB) jitter components, which are considered to occur at frequencies above 36 Hz exclusive of the chopper band. Small amplitude OOB jitter components make a negligible contribution to the radiometric jitter noise. For large amplitude OOB jitter components, the nonlinear altitude dependence of the radiance profile leads to the generation of frequency harmonics. The frequency spectrum of these harmonics contains sum and difference frequencies between two or more OOB jitter components and doubling of OOB frequency components. Thus, it is possible that some of the OOB frequency harmonics will fall within the chopper band or the signal band. To first order, the resulting radiometric error will have an altitude dependence that follows the second derivative of the radiance profile. The magnitude of the error will depend in a rather complex way on the amplitudes of the components, the total frequency range of OOB jitter components and the electrical bandwidths used in the signal processing.

Finally, a word about the signal bandwidth since it has important implications for the design of the optical bench mounts, and in particular where in frequency the principal resonance of these mounts should occur. In the global mode of observation, the signal band (or measurement band) has been defined in the IRD to be nominally 7.5 Hz. This number arises from a desire to measure, as a minimum, spatial features in the radiance profile having wavelengths of 2-km or longer, given the 1-km vertical FOV. For a scan rate at the tangent point of 15 km/s (approx. 0.3 °/s), a 2-km wavelength corresponds to a temporal frequency of 7.5 Hz. The first null in the spatial frequency response for an ideal rectangular FOV having a full width of 1-km corresponds to a temporal frequency of 15 Hz. The actual observable spatial frequencies having a signal-to-noise ratio above one will occur somewhere between 7.5 and 15 Hz - probably around 10 or 11 Hz based on the expected noise level and the predicted MTF of the telescope (see for example the recent Payload Panel Meeting and CHEM-1 Study viewgraphs). Note that a signal bandwidth of 15 Hz was used as a convenient upper limit in the analyses presented in this TC. The effect of jitter for an increased or a decreased signal bandwidth, *B*, can be estimated by scaling the results reported here using $noise(B\ Hz) = noise(15\ Hz)\sqrt{B/15\ Hz}$, and assuming a flat jitter noise spectrum over the particular frequency range of interest.

Since HIRDLS limb radiance measurements are especially sensitive to LOS motions having frequencies falling within the nominal 10 to 15 Hz signal band, it is important to minimize spacecraft input at these frequencies. Having a bench mount whose resonance occurs within the signal band results in an amplification of LOS motion near the resonant frequency by perhaps a factor of 5 to 10. Therefore, it seems prudent to push the resonance of the mounts to well above the signal band. Where in frequency depends upon the maximum signal bandwidth that is expected. If the scan rate is tripled, as might be the case for the fastest scan rate, the lowpass filter bandwidth will need to be increased, but because of the increased radiometric noise, only to approximately 30 Hz. The penalty for doing this is a $\sqrt{3}$ increase in both radiometric noise and jitter noise (this assumes a nominal global mode signal bandwidth of 10 Hz). This would tend to suggest a mount having a resonant frequency above 35 or 40 Hz where the radiance measurements are fairly insensitive to uncertainties in LOS motion.

Calculation of Jitter Noise Using HIRAM

To evaluate jitter noise and in particular, noise due to out-of-band jitter, LOS jitter errors were modeled in HIRAM. The unaltered tropical fiducial atmospheric radiance profiles (SP-HIR-90A) were used as input to HIRAM. The fiducial radiance profiles were generated to be used to verify any instrument requirements that depend upon the magnitude and altitude dependence of limb radiances. The atmospheric temperature, pressure and constituent concentration profiles used to produce these radiance profiles are representative of the annually averaged conditions at 15° N latitude. The very warm lower boundary in this case produces a relatively strong radiance gradient near the tropopause and should therefore provide a fairly stressing condition for jitter studies. Other atmospheric conditions, such as enhanced aerosol loading or the presence of PSCs and high cirrus clouds which produce locally steep radiance gradients, will likely produce a greater contribution to radiometric noise from jitter at altitudes near the cloud or aerosol layer than the maximum jitter noise reported here, particularly for the optically thin channels.

The scan mirror motion converts the altitude profile into a time-dependent radiance signal. This is modeled in the HIRAM routine *scan.f* using the following relationship between altitude and time,

$$z = v_{sc}\,(t_o + i \cdot dt) \quad , \quad i = \ 1,\ 2,\ 3,\ \ldots$$

where v_{sc} is the scan rate at the tangent point, assumed to be constant, and dt is the model time step determined by the desired number of points per chopper cycle, i.e. $dt = 1/(n \cdot 500\,Hz)$. For example, 8 points per chopper cycle was used for the simulations giving a time step of 0.25 msec with a corresponding altitude step of 3.75 m for the global mode scan rate (taken to be 15 km/s). The assumption that the scan rate is constant over the elevation scan simplifies the modeling problem, but does not affect the jitter analysis. In practice the scan mirror motion will vary a small amount over an elevation scan. The implicit assumption within HIRAM is that the scan mirror encoders track mirror motion exactly, reading out a change in scan mirror angle, $\Delta\alpha_{sc}$, which can be exactly related to a change in tangent height. Any uncertainties in this process are considered to be lumped in with the pointing/jitter error. Changes in tangent height due to pointing and jitter errors are modeled as perturbations to the local tangent height, i.e. $\Delta z = R_t\ \Delta\alpha(t)$, where $\Delta\alpha(t)$ is the random change in LOS angle.

The fiducial radiance values in SP-HIR-90A are given in 1-km intervals. The 1-km spacing is too coarse for HIRAM, so the profiles are interpolated, using a spline fit (IMSL library routine CSAKM), onto a finer uniform altitude grid. This particular spline interpolation routine was chosen because of its property to minimize oscillations produced by rapidly varying functions. These oscillations are seen in more commonly used cubic spline routines such as the Numerical Recipes SPLINE, SPLINT routines. The interpolation interval, *dz*, is determined by the time step and by the scan rate specified in the HIRAM simulation (i.e. $dz = v_{sc}\, dt$). The spline interpolated fiducial radiance profile is considered to be the true radiance profile and used as input to the HIRAM model. The radiometric jitter noise is determined by comparing the model output radiance profile containing jitter errors to the true (interpolated) radiance profile.

The input radiance profile is then spatially smoothed by the IFOV response function in the HIRAM routine *telspa.f.* The spatially smoothed radiance signal is passed to the *telrad.f* routine which models the radiometric effects of fore-optics. The effects of pointing and jitter errors are modeled in this routine. Jitter error is modeled as a perturbation to the radiance signal. The radiometric jitter noise is calculated for every point in the limb scan by interpolating the input radiance profile at the point $z + \Delta z$ and taking the difference between the nominal radiance value, $N(z)$ given by the smoothed fiducial radiance profile, and the "jittered" radiance, i.e.

$$\Delta N = N(z+\Delta z) - N(z) \quad , \quad \Delta z = R_t\, \Delta\alpha(t) \ .$$

The uncertainty in relative LOS angle, $\Delta\alpha(t)$, is modeled by a random time sequence whose spectral content is shaped (or "colored") by a power spectral density (PSD) function. This means the instantaneous value of the perturbed LOS angle will vary with time, or equivalently with altitude. The rate of change of $\Delta\alpha(t)$ between sample points will be determined by the frequency content of the random sequence. The random LOS sequence is produced by applying a transfer function, defined by the specified single-sided PSD, to a random white noise spectrum, i.e.

$$PSD_\alpha(f) = 2 \cdot S_w \left|H(f)\right|^2 \quad , \text{ in (arcsec}^2\text{) / Hz}$$

where S_w is an ideal double-sided white noise power spectrum and $|H(f)|^2$ is the power transfer function used to shape the white noise spectrum. The factor of 2 in the above equation comes the conversion from a double-sided spectrum used in the HIRAM calculation to a single-sided spectrum used to specify the desired PSD. The magnitude of the white noise spectrum is fixed such that its mean-square power is 1 $arcsec^2$ over the frequency range from zero to f_{max}, where f_{max} is Nyquist frequency of the Discrete Fourier Transform (DFT) calculation. The white noise term given above is essentially a scaling factor that accounts for the finite frequency bandwidth of the DFT calculation.

The single-sided jitter PSD is modeled in a piecewise fashion by specifying a desired rms level over a given low frequency bandwidth (e.g. 0.7" rms, 0-15 Hz), a desired OOB rms jitter level between low and high frequency corners, and a final PSD slope above the OOB high frequency corner. An example of an LOS jitter PSD is shown in Figure 3. The gain or loss of the piecewise sections of the transfer function can be adjusted by specifying the equivalent rms value and frequency range of the section, i.e.

$$|H_o|^2 = \frac{A_{rms}^2}{(2\,S_w\,f_s)} \quad , \quad |H_1|^2 = \frac{B_{rms}^2}{(2\,S_w\,(f_3 - f_2))}$$

where A_{rms} is the desired rms value of pointing error over a given signal bandwidth f_s and B_{rms} is the desired rms value of OOB jitter over the frequency range from f_2 to f_3. The slope of the transfer function from the low frequency section to the OOB section is calculated. The final roll-off is specified. The transfer function is applied to a random white noise spectrum generated by allowing the real and imaginary components to be random variables,

$$F_W(f) = \tfrac{1}{\sqrt{2}}(X(f) + jY(f)) \ .$$

X and Y are random variables having gaussian distributions, unit standard deviations and zero means. The "shaped" noise spectrum is then

$$F_\alpha(f) = \ F_W(f)\,|H(f)| \ .$$

The angle spectrum is forced to be hermitian (i.e. the real part of the spectrum must be even and its imaginary part must be odd) which in turn forces the final output sequence to be real-valued. The resulting LOS angle spectrum is then inverse Fourier transformed to produce a random time-varying sequence, i.e. $\Im^{-1}\{F_\alpha\} = \ \alpha(t)$.

As a check, the above procedure was used to generate a random sequence of relative LOS angles in HIRAM. The process was then taken in the reverse direction by estimating the jitter PSD of the random sequence using Welch's method[2]. The comparison between the specified PSD and the calculated PSD is remarkably good. This, along with comparisons of calculated and desired rms values for lowpass and bandpass cases, is considered to be reasonable validation that the noise generator routine used in HIRAM to model the effect of random jitter is sufficiently good.

[2] Welch's method - The PSD is estimated by breaking the time series into several segments of equal length, applying a data "window" to each segment and then computing the PSD of each "windowed" segment. Finally, the PSDs of each segment are averaged together. (Welch, IEEE Trans. AU-15, 1967).

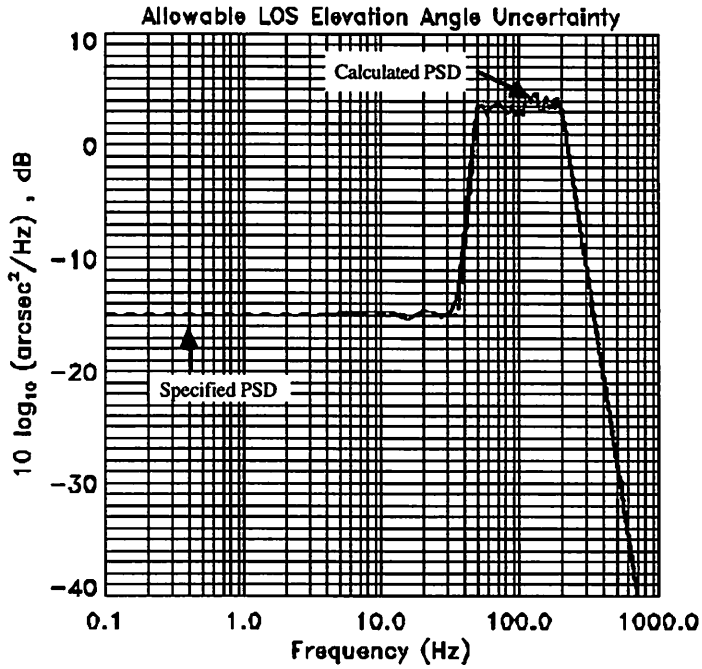


Figure 3. A check of the random LOS jitter routine used in the HIRAM model. Shown is the specified PSD used to generate a random time sequence of LOS perturbation angles and the PSD estimated from this same time sequence using Welch's method.

The radiance signal passes through several other HIRAM modules where the signal is chopped, detected, analog bandpass filtered and synchronously sampled. The demodulated output samples are digitally lowpass filtered to produce the final instrument output samples as a function of time. These output samples are converted into radiance values using the averaged IFC sample counts and the averaged space view counts. Altitude levels are assigned by fixing the first limb radiance sample to 0 km plus some calculated delay due to the relative phase between chopping and sampling, and the fixed delay of the digital filter. Altitude levels for the subsequent radiance samples are built up by knowing the number of points per chopper cycle, the scan rate, and the final output sample rate.

The HIRAM model is run several times with a new random LOS jitter sequence generated for every simulation. A mean output radiance profile, $\overline{N}(z)$, is calculated by averaging over the m individual HIRAM simulations, $N_i(z)$, i.e.

$$\overline{N}(z) = \frac{1}{m}\sum_{i=1}^{m} N_i(z) \quad .$$

The variance of the individual simulations about this mean profile is calculated at every 0.2 km altitude point. The systematic and random errors for a given altitude are defined by

$$\text{systematic error} = \overline{N}(z) - N(z)$$

$$\text{random error} = \left[\frac{1}{(m-1)}\sum_{i=1}^{m}(N_i(z) - \overline{N}(z))^2\right]^{\frac{1}{2}} .$$

where *N(z)* represents the true input radiance profile. In the HIRAM calculation, other sources of radiometric noise are set to zero, so the random error that is calculated is due solely to pointing and jitter errors.

Radiometric Sensitivity to LOS Jitter Errors

In this section, the radiometric sensitivity to various components of LOS elevation angle uncertainty (i.e. pointing errors, in-band jitter, etc.) is investigated using HIRAM. The relationship between pointing error and radiometric error is well understood. However, HIRAM calculations of pointing errors serves as a useful check for the model and this is presented first for Channel 3. Channel 3 is chosen as representative of the four temperature sounding channels. The sensitivity to "in-band" jitter noise for Channel 3 is investigated next. Essentially, "in-band" jitter noise is indistinguishable from pointing errors after signal processing, and has a very similar functional relationship between LOS errors and jitter noise. The difference being a small factor accounting for the chopping waveform and the appropriate bandwidth of the chopping band is two times the signal bandwidth.

Finally, the sensitivity to out-of-band LOS jitter errors is investigated. The first case discussed is a worst case, or at least near worst case, example of OOB jitter for Channel 3. A somewhat more relevant case is then discussed for channels 3 and 8, based on OOB levels defined by the suggested LOS jitter PSD requirement to be discussed later. In this final case, the frequency band containing OOB jitter components is significantly narrower than the worst case example given for channel 3, but with a comparable rms value.

A. Pointing Error

A comparison of the HIRAM calculation with a theoretical estimate of jitter noise for Channel 3 is made, principally as a check of the HIRAM calculation. Here a simple lowpass LOS angle PSD is defined such that it is spectrally flat over the "pointing band" from 0 to 36 Hz with an rms error equal to 0.7 arcsec over the 15 Hz signal band. The LOS PSD falls off rapidly above 36 Hz (see Figure 4.). In this case, the maximum radiometric jitter noise is expected to occur near 30 km (see Appendix I) with a magnitude of

$$(5.5 \text{ x } 10^{-2}\ W/m^2\ sr/km)\cdot(14.5 \text{ x } 10^{-3}\ km/arc\text{sec})\cdot(0.7\ arc\text{sec})/(5.9 \text{ x } 10^{-4}\ W/m^2\ sr) = \underline{0.95\ NEN}\ .$$

The HIRAM calculation of jitter noise corresponding to this simple lowpass jitter PSD is shown in Figure 4, given by the solid line. The calculation shows a peak in the jitter noise near 30 km of approximately 1.0 NEN, close to the expected value. Also shown for reference in this figure is the IRD 1 arcsec limit, given by the dashed line .

B. In-band Jitter Errors

In-band jitter noise is given by the product of the radiance slope and the rms value of the tangent height error, integrated over two times the signal band centered about the chopping frequency. In-band jitter noise is slightly reduced by the ratio of the average value of the chopping waveform and the amplitude of its fundamental. Jitter noise due solely to in-band LOS jitter will be a maximum where the slope of the radiance profile is a maximum, just as with the pointing error. That is exactly what is seen in the HIRAM calculations. For channel 3, this maximum occurs near 30 km. The HIRAM calculations for 3 levels of in-band jitter along with the theoretical estimates of maximum jitter noise are summarized in Table 1.

Table 1.

Channel 3 jitter noise due to LOS jitter at frequencies 500 ± 15 Hz.

In-Band Jitter (arcsec rms)	Calc. max. jitter Noise (NEN)	Theoretical max. jitter Noise (NEN)
0.25	0.3	0.3
0.5	0.7	0.6
1.0	1.1	1.2

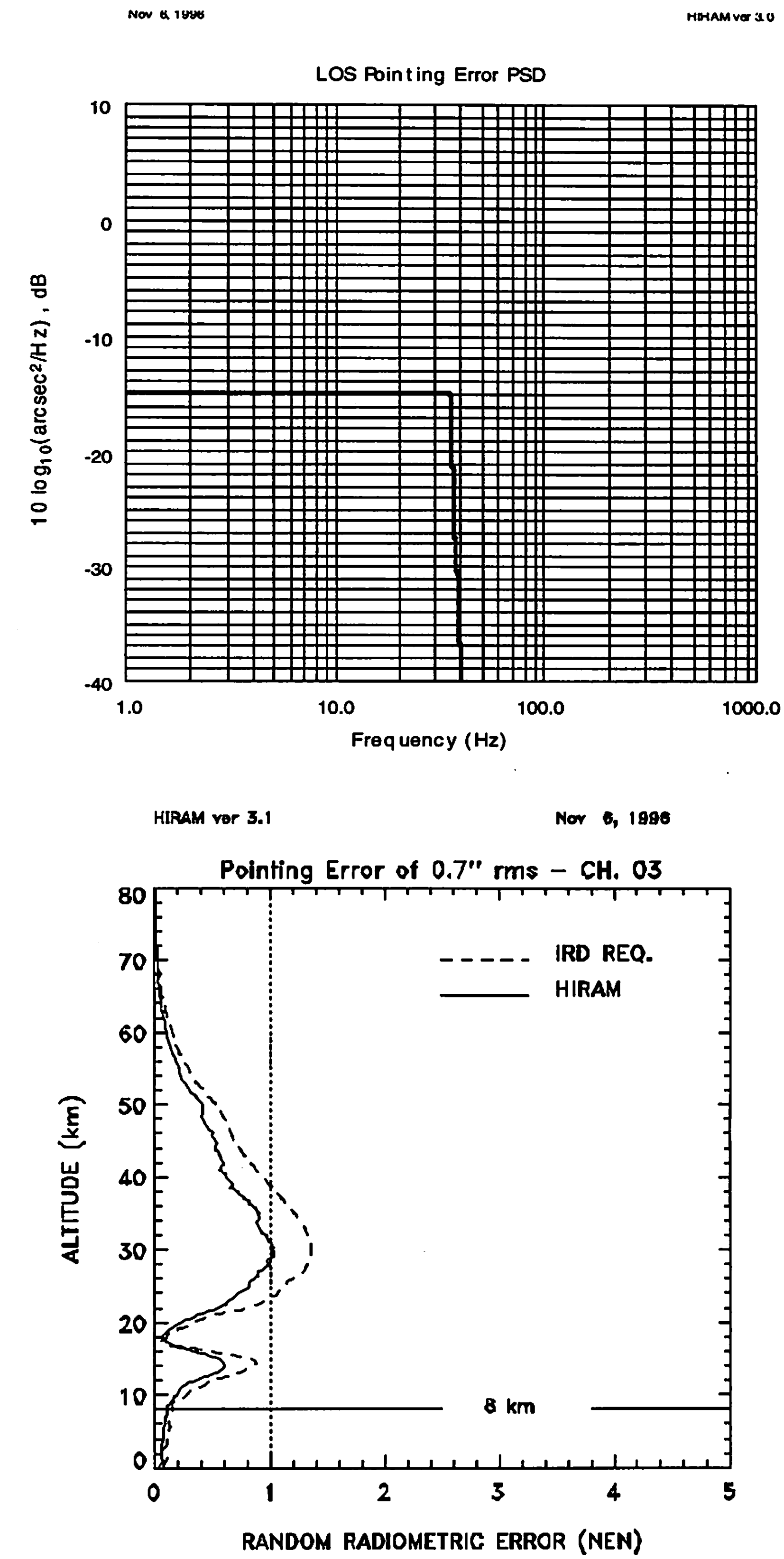


Figure 4. HIRAM simulation for Channel 3 of random radiometric error due to pointing error. The top panel defines the LOS pointing error PSD used in the calculation. The rms value of pointing error integrated over the 0 to 15 Hz signal bandwidth is 0.7 arcsec. The bottom panel shows the resulting random radiometric error. In the bottom panel, the dashed line represents the 1 arcsec rms IRD limit for reference.

C. Out-of-Band Jitter Errors

The effect of out-of-band jitter was modeled by defining the LOS elevation angle PSD such that it had a well defined rms value over a given frequency range which fell outside of the signal and chopper bands. In other words, pointing error and in-band jitter were zero. The OOB jitter PSD was defined, in this case, as having a spectrally flat level between 50 and 400 Hz with corresponding rms values of 5, 10, and 20 arcsec for the three separate calculations[3]. The PSD then falls off rapidly on either side of the frequency range.

The radiance profile for channel 3 shows a maximum in the second derivative near 16 km. The other temperature channels show second derivative maxima of roughly the same magnitude, but occurring at different altitudes. The results of the HIRAM calculation for Channel 3 are summarized in Table 2. Note for the OOB jitter level corresponding to 20 arcsec rms, a noticeable systematic error is produced in the HIRAM calculation. To some extent, this will appear as a constant altitude offset which will be partially removed by the retrieval process. The systematic error due to large amplitude OOB jitter has not been investigated in detail. Plots of Channel 3 OOB jitter noise for the three LOS jitter cases given in Table 2 are shown in Figure 5. Note that the maximum jitter noise occurs where the second derivative is largest, near 16 km and there is a secondary maximum near 22 km. These results should be fairly representative of the sensitivity of the temperature sounding channels to OOB jitter.

Table 2.

Channel 3 jitter noise due to out-of-band LOS jitter at frequencies 50 to 425 Hz.

OOB Jitter (arcsec rms)	Max. Jitter Noise (NEN)	Alt. of Max. Noise	Max. Systematic Error (%) at 60 km
5	0.03	16.2 km	< 0.01
10	0.11	16.6 km	0.03
20	0.48	16.2 km	0.11

3 The mean-square power within a given frequency range is determined by integrating the single-sided PSD over that range. The rms value is just the square root of the mean-square power.

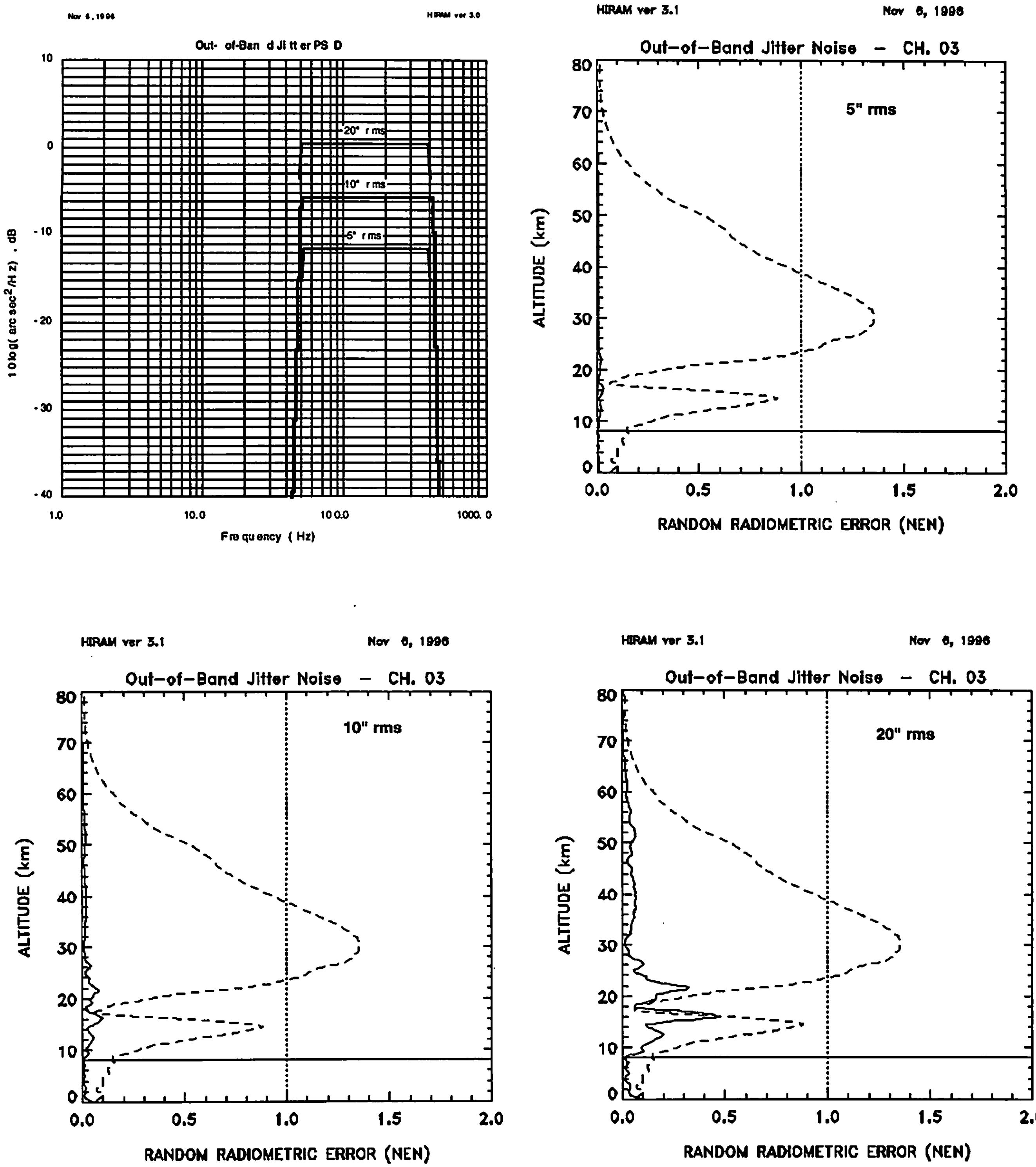


Figure 5. Examples of radiometric sensitivity of Channel 3 to out-of-band LOS jitter. The top panel shows the PSDs for the three cases and the results for 5 arcsec rms OOB jitter over 50 to 425 Hz. The bottom panel shows results for the 10 arcsec rms and 20 arcsec rms cases. The dashed line is the IRD 1 arcsec jitter limit.

The sensitivity of the several of the constituent channels to OOB jitter is greater than that of the temperature sounding channels, particularly for the optically thin channels such as channel 8, 10, 12 and 18. Many of these channels have rapidly varying radiance slopes at the lowest altitudes which of course leads to large second derivatives. Channel 8, which appears to be one of the more sensitivity channels to jitter, is used as a worst case example for OOB sensitivity. Also, a more relevant out-of-band jitter PSD is defined for this example which consists of only the OOB frequency components of the final LOS jitter requirement to be presented later (see Figures 6a and 7). HIRAM calculations of jitter noise for Channels 3 and 8 are summarized in Table 3. Channel 3 was chosen for comparison with previous calculations. Also for comparison in the Table is the equivalent error for 1 arcsec of jitter corresponding to the same altitude where the OOB jitter noise is a maximum. Plots of OOB jitter noise for these two channels are shown in Figure 6b.

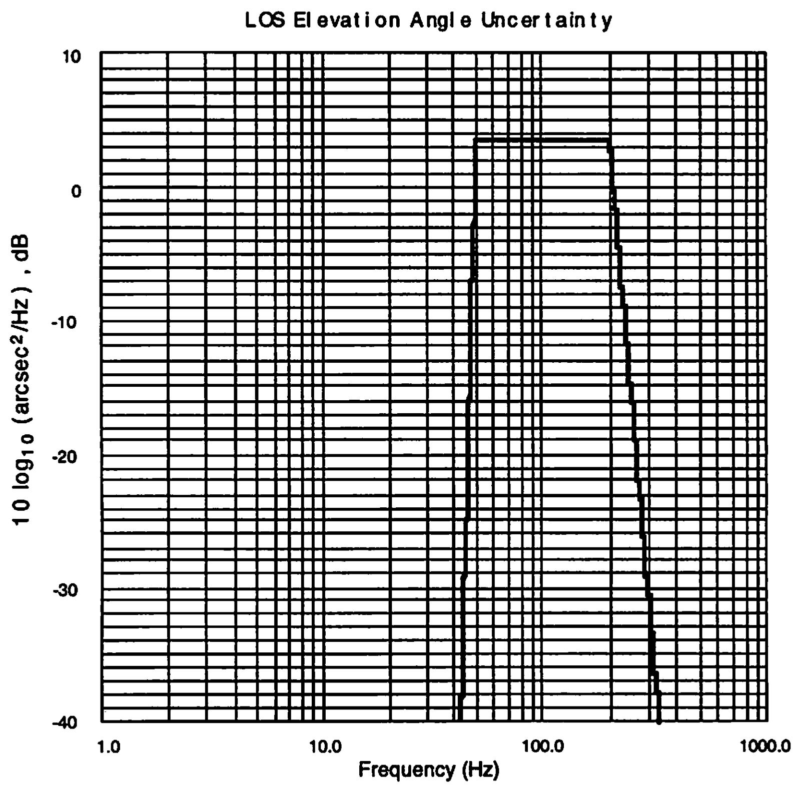


Figure 6a. Out-of-band LOS jitter PSD.

Table 3.
Jitter noise due to 18.3" rms OOB LOS jitter over 50 to 200 Hz.

Channel No.	Max. Jitter Noise (NEN)	Alt. of Max. Noise	Effect of 1" jitter at max. altitude (NEN)
3	0.5	16 km	0.5
8	6	9.5 km	7

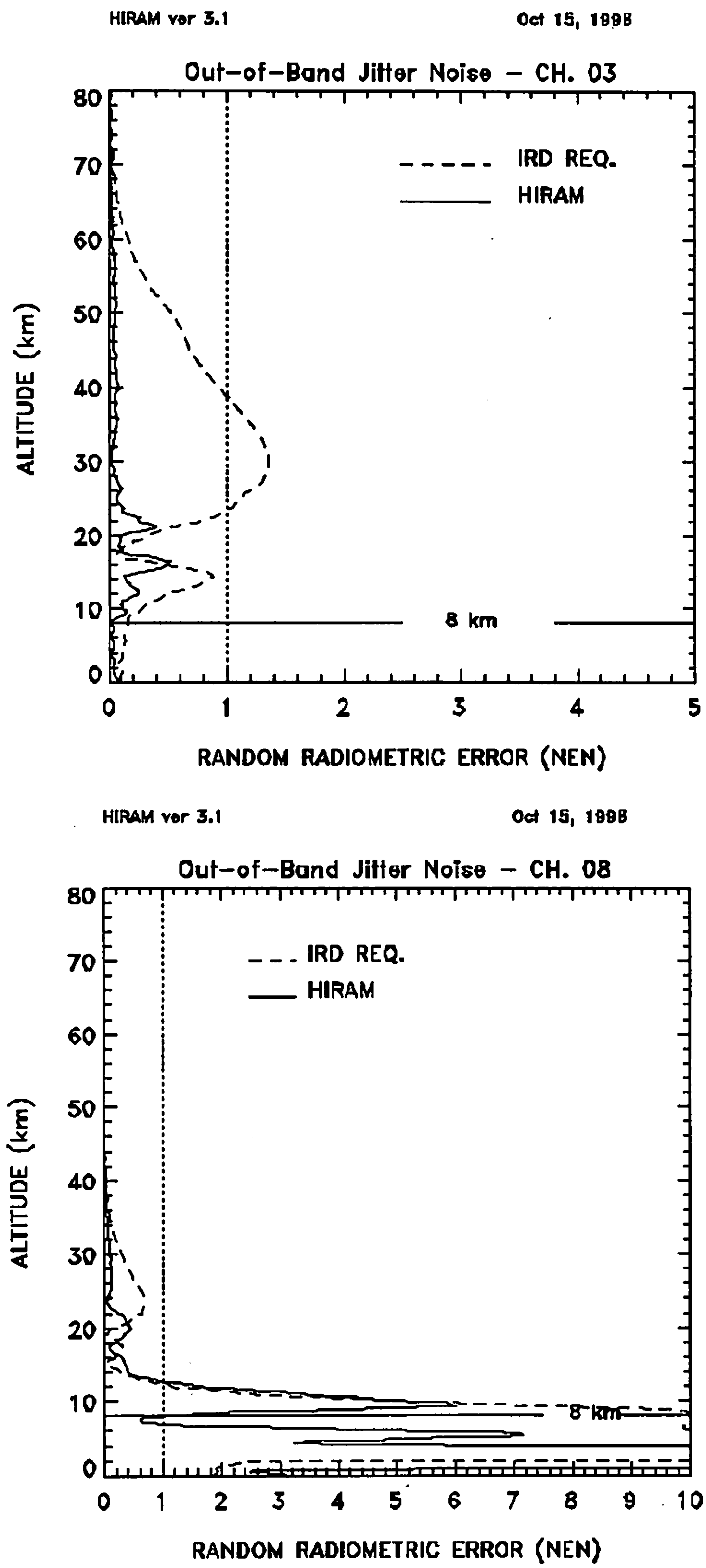


Figure 6b. HIRAM calculations of out-of-band jitter noise for Channels 3 and 8 using the LOS jitter PSD defined in Figure 6a.

Allowable LOS Elevation Angle Jitter Requirement

The approach taken to define an ITS-level LOS elevation angle jitter requirement was to set a requirement such that the total radiometric error due to both pointing and jitter errors was less than or equal to the radiometric error corresponding to the IRD requirement of 1 arcsec rms LOS angle uncertainty over a 7.5 Hz bandwidth. The IRD limit can be described mathematically by the expression:

$$\Delta N(rms) = \left(\frac{\partial N}{\partial z}\right)\sigma_{\Delta z}(rms) \quad , \quad \sigma_{\Delta z}(rms) = 14.5\ m \ .$$

The reason for taking this approach is that the science requirements have been verified to be met for a number of important channels (see for example SCR viewgraphs of retrieval simulations for temperature, ozone and water vapor in the presence of radiometric noise and jitter) based on the IRD requirement and the assumption that the altitude dependence of jitter noise follows the slope of the radiance profile, i.e. no second order or higher derivative dependence. The assumption is that if the jitter noise resulting from any new definition of LOS jitter error remains below the IRD limit, the science requirements on precision will still be met with reasonable confidence.

In order to set a new LOS elevation angle jitter requirement, the following steps were taken :

1.) Assume the pointing error integrated over the 15 Hz signal bandwidth is 0.7 arcsec rms,
2.) set the out-of-band jitter level to envelope the most recent LOC jitter analysis from 50 to 200 Hz, and
3.) set the final roll-off to be -80 dB/decade.

Recent LOC vibration analyses performed by Alain Carrier showed strong resonances due to TSS translational and flexure modes occurring at 70, 120, and 134 Hz. This analyses assumed a 50 Hz hard mount which gives very little attenuation against excitation of these TSS vibrational modes. The LOS errors calculated by Alain appear to fall off quite rapidly above 134 Hz. Therefore, the idea was to try setting a PSD requirement that enveloped the LOC analysis in this frequency region and then to calculate what the resulting jitter noise would be. In earlier analyses, the jitter PSD had been overly constrained by choosing a final -20 dB/decade roll-off. The result of this was to constrain the OOB jitter level by the required level of in-band jitter, not by the level of OOB that be could tolerated. The jitter PSD requirement reported here does appear to set an approximate upper limit to the OOB jitter that can be tolerated.

Given this approach, the allowable LOS elevation angle jitter PSD is shown in Figure 7. The jitter requirement is defined only above the nominal 36 Hz gyro cutoff (solid line). However, since some assumption about pointing error must be made in order to verify that the 1 arcsec IRD requirement is met, the jitter PSD also shows a pointing error PSD level below 36 Hz (dashed line). Taken together, this defines the allowable LOS elevation angle uncertainty. Table 4 gives a piecewise description of the jitter PSD. Table 5 gives integrated values, in terms of rms quantities, over the specified frequency ranges. These ranges correspond to the jitter definitions used in the SPRAT and current ITS.

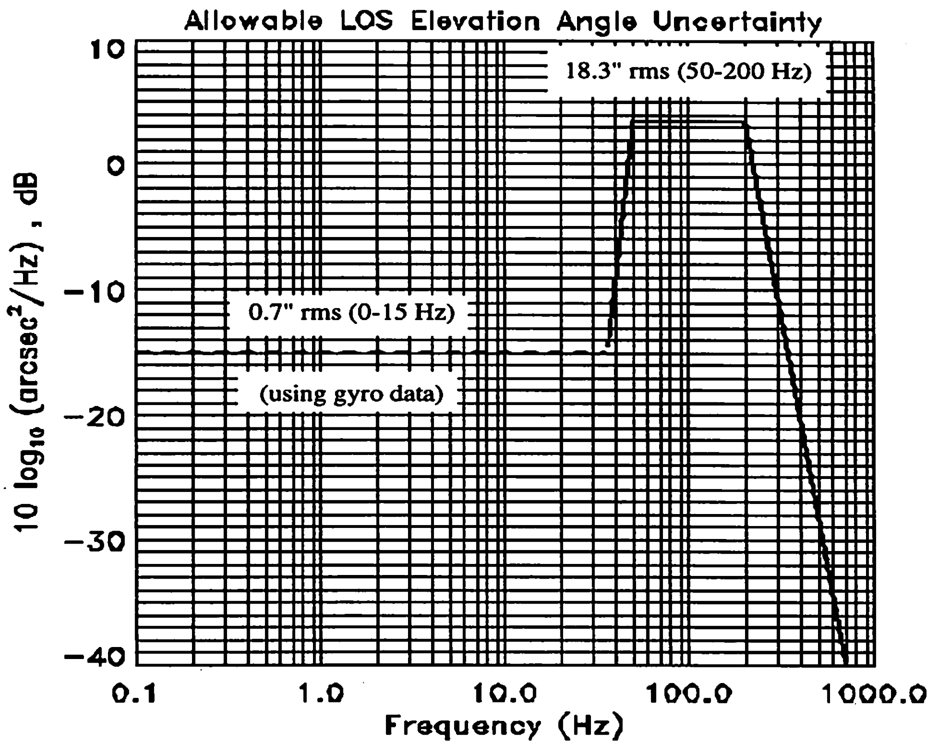


Figure 7. Single-sided PSD defining the allowable LOS elevation angle random uncertainty. The dashed line represents the pointing error after all calibration and correction factors have been applied. The solid line represents the elevation angle jitter requirement relative to inertial space and for all azimuth angles. The PSD assumes a 0.1 Hz LOS jitter measurement bandwidth.

Table 4. Piecewise description of LOS angle uncertainty PSD.

Frequency (Hz)	PSD (dB)	slope (dB/decade)	PSD (arcsec²/Hz)
< 0.1	—	-80	—
0.1 - 36	-14.9	0	0.0327
36 - 50	—	~ 80	—
50 - 200	+3.5	0	2.239
> 200	—	-80	—

Table 5. Integrated LOS angle uncertainty levels.

Frequency (Hz)	Integrated jitter (arcsec rms)	reference to TC-OXF-98
0 - 15	0.7	"pointing" error
50 - 200	18.3	"out-of-band" jitter
485 - 515	0.2	"in-band" jitter
0.1 - 1000	20.6	Total integrated jitter

Resulting Radiometric Jitter Noise - *Channels 1-5 , 8, 10-12, and 18*

The LOS elevation angle uncertainty PSD shown in Figure 7 was used in HIRAM calculations of jitter noise for Channels 1-5, 8, 10-12, and 18 to verify that this requirement still meets the original 1 arcsec IRD requirement. The following conditions were used in the calculation:

* 8 points per chopper cycle.
* 50 simulations were used in calculating the rms random error.
* unaltered tropical fiducial radiance profiles SP-HIR-90A) were used.
* all other radiometric noise sources (e.g. detector noise) set to zero.
* all systematic radiometric errors (slope and zero errors) set to zero.
* bandwidth of analog bandpass filter is 250 to 750 Hz.
* baseline synchronous sampling scheme used.
* noise bandwidth of the lowpass digital filter equal to 15.5 Hz.
* chopping frequency equal to 500 Hz; output sample rate equal to 84 Hz.
* constant scan rate equal to 15 km/s at tangent point.

The results of the HIRAM calculations of jitter noise for channel 1 and the four temperature sounding channels 2-5 are shown in Figures 8a-c. Jitter noise calculations for Channels 8,10, 12, and 18 are shown in Figures 9a-c. The dashed-line represents the IRD 1 arcsec rms requirement. Over much of the sounding ranges of interest, the random radiometric error (jitter noise) falls below the IRD requirement limit with only small encroachments at a few altitudes, but for the temperature sounding channels this occurs where the jitter noise levels are relative small and causes little concern. Unfortunately for channels 8, 10 and 12, the sensitivity to jitter errors near the bottom of their sounding ranges is exacerbated by the additional OOB jitter effects.

The present jitter PSD requirement has evolved from earlier jitter analyses to allow for a much higher level of out-of-band jitter. This level of OOB jitter probably represents the upper limit on what can be tolerated without some impact to the science requirements, particularly for retrievals of HNO_3, O_3 and H_2O in the lower stratosphere/upper troposphere.

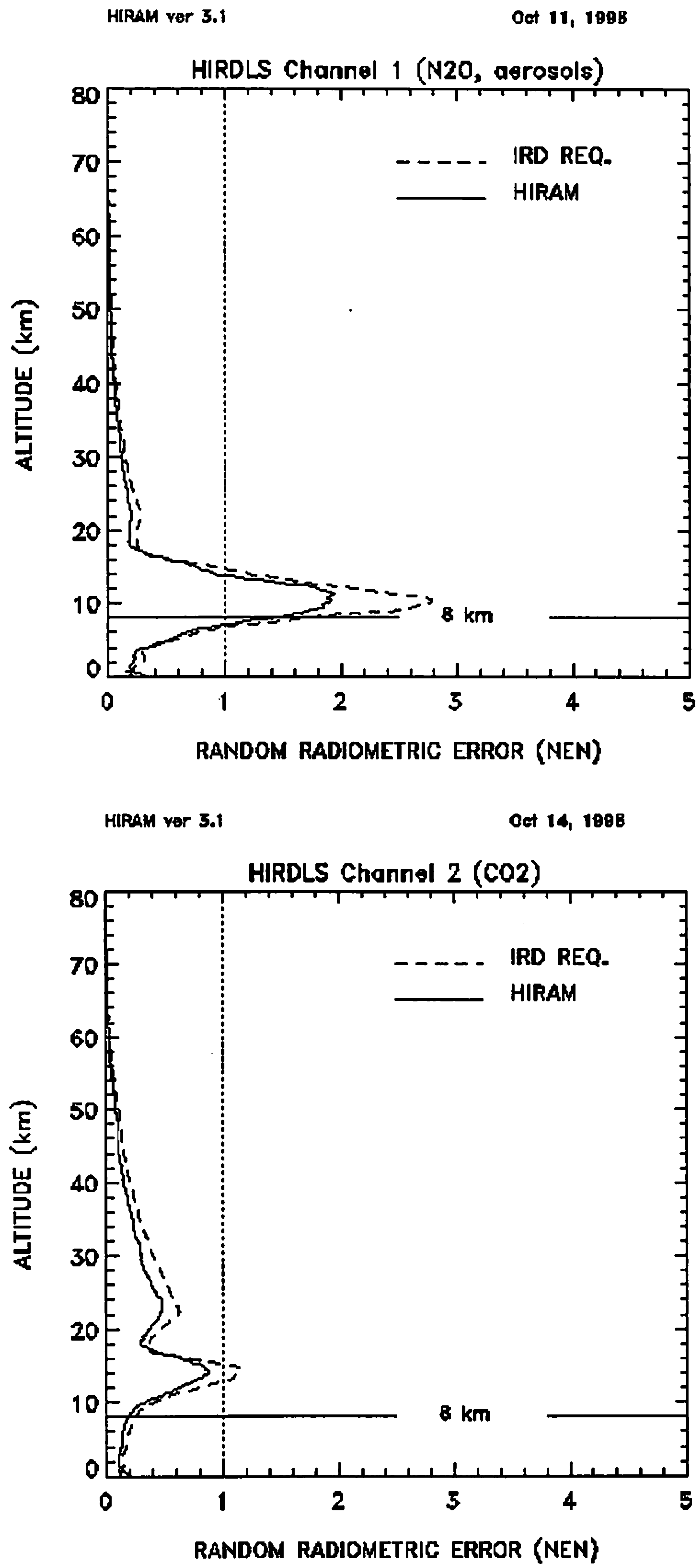
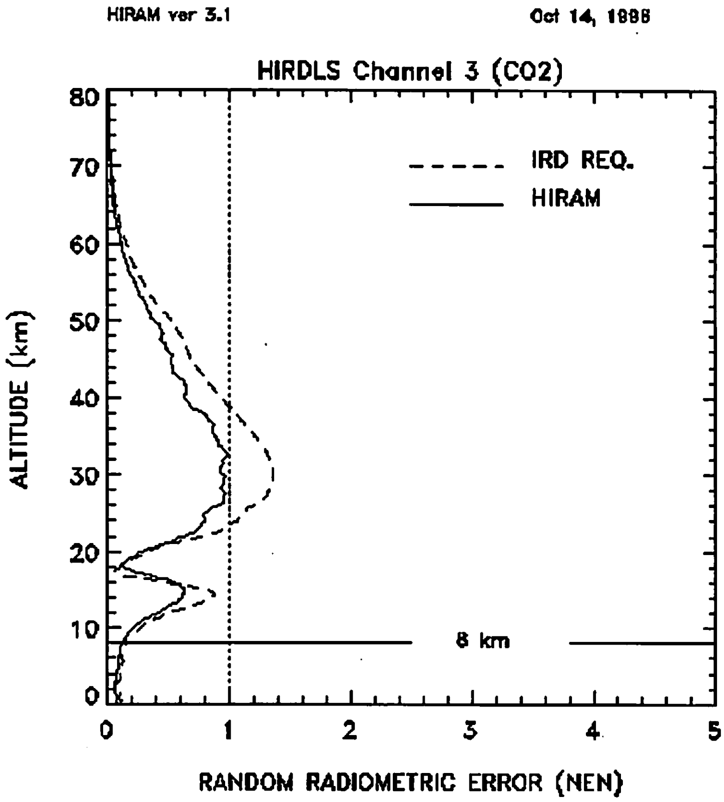


Figure 8a. Calculated radiometric jitter noise for HIRDLS channels 1 and 2 (solid line) based on the allowable LOS elevation angle PSD given in Figure 7. Jitter noise corresponding to the IRD requirement of 1 arcsec rms is shown by the dashed line.



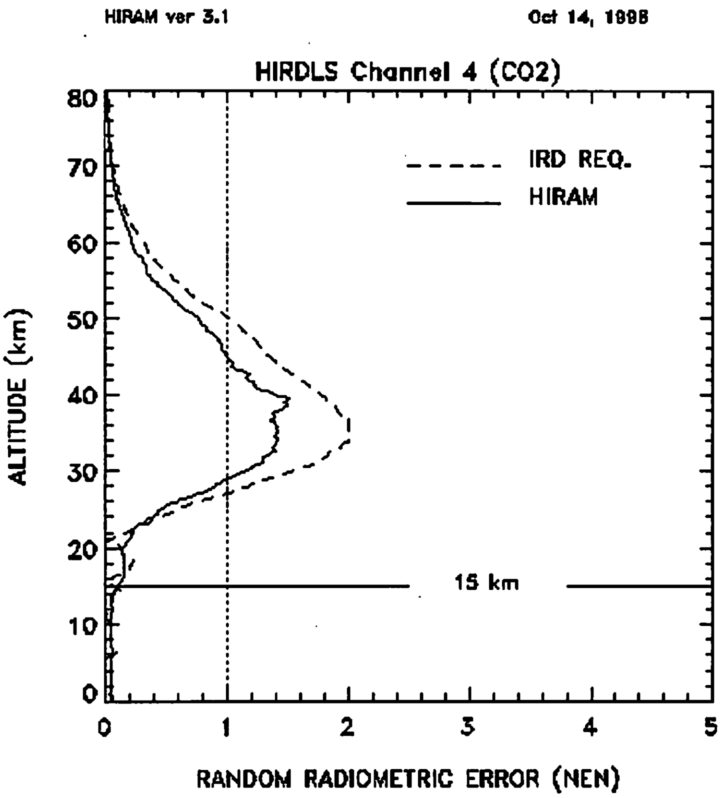


Figure 8b. Calculated radiometric jitter noise for HIRDLS channels 3 and 4 (solid line) based on the allowable LOS elevation angle PSD given in Figure 7. Jitter noise corresponding to the IRD requirement of 1 arcsec rms is shown by the dashed line.

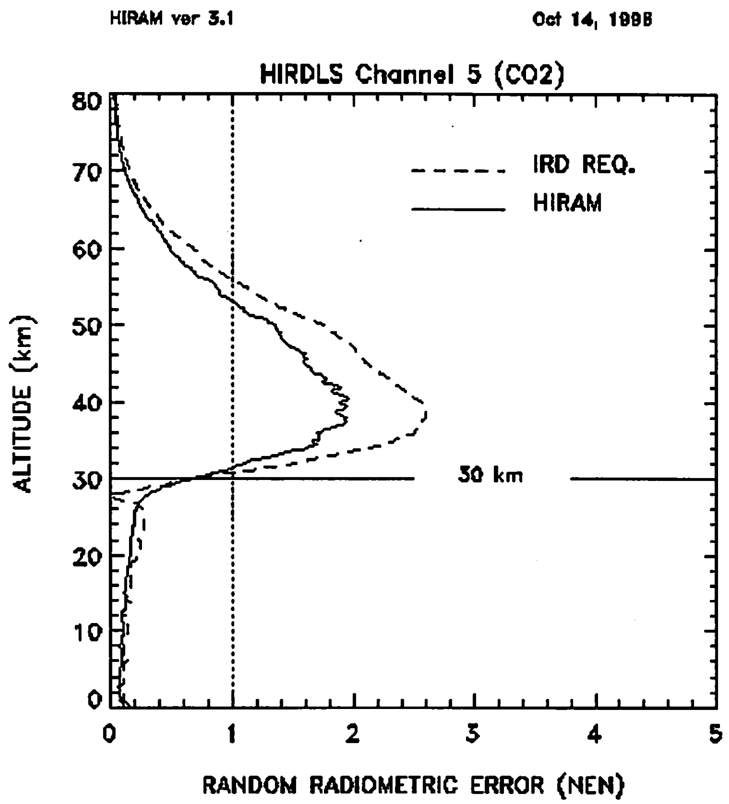
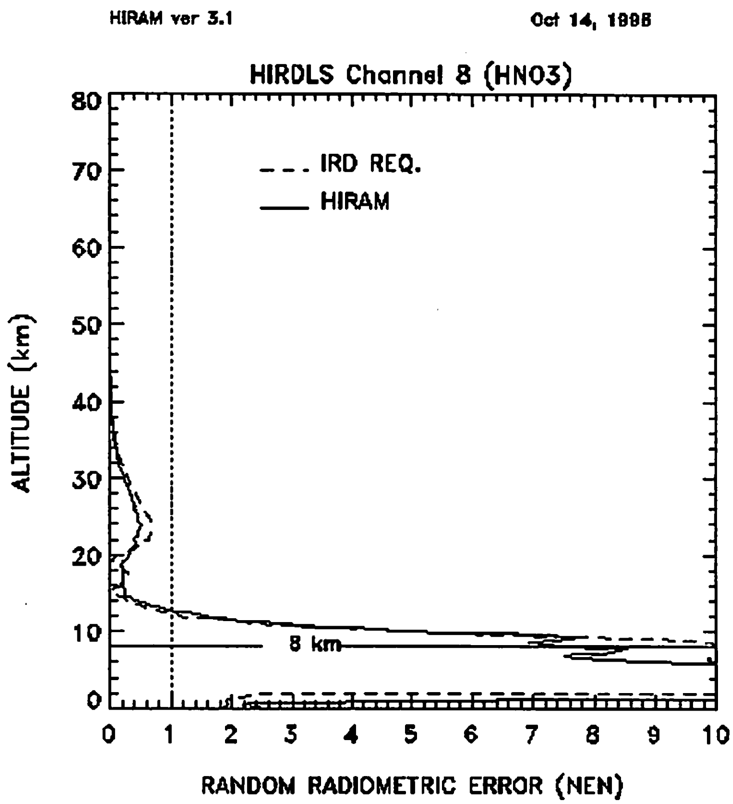


Figure 8c. Calculated radiometric jitter noise for HIRDLS channel 5 (solid line) based on the allowable LOS elevation angle PSD given in Figure 7. Jitter noise corresponding to the IRD requirement of 1 arcsec rms is shown by the dashed line.



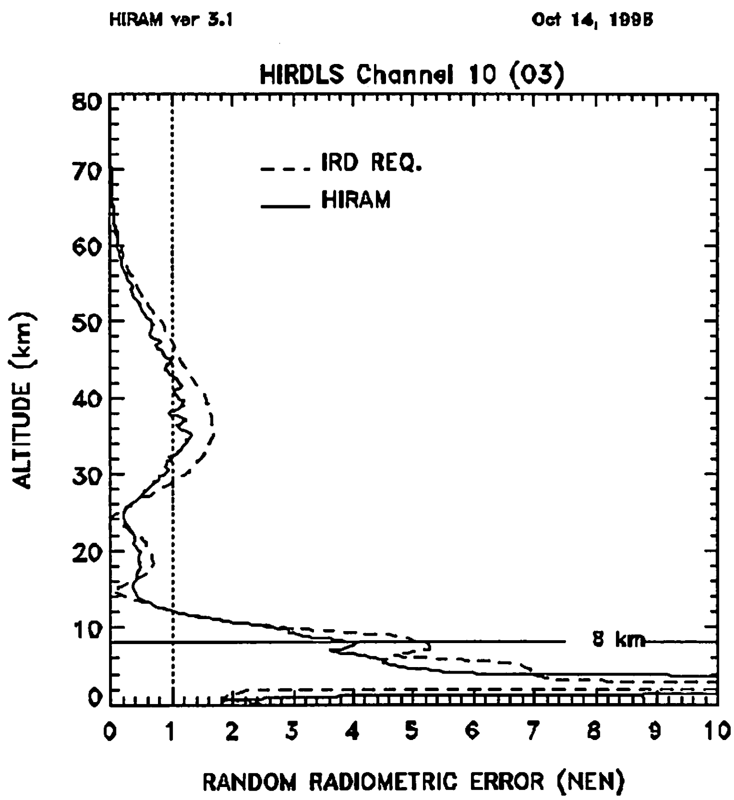
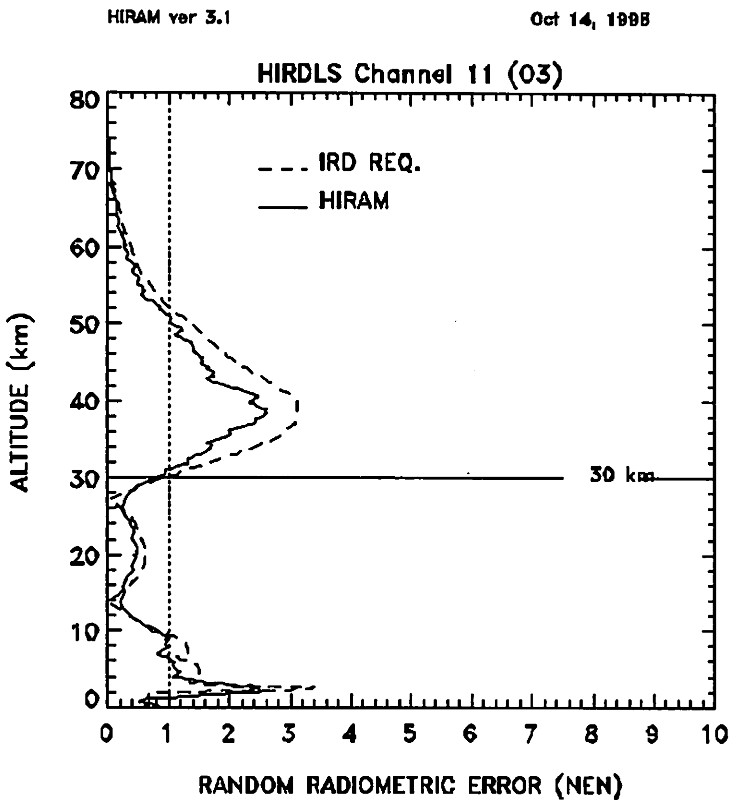


Figure 9a. Calculated radiometric jitter noise for HIRDLS channels 8 and10 (solid line) based on the allowable LOS elevation angle PSD given in Figure 7. Jitter noise corresponding to the IRD requirement of 1 arcsec rms is shown by the dashed line.



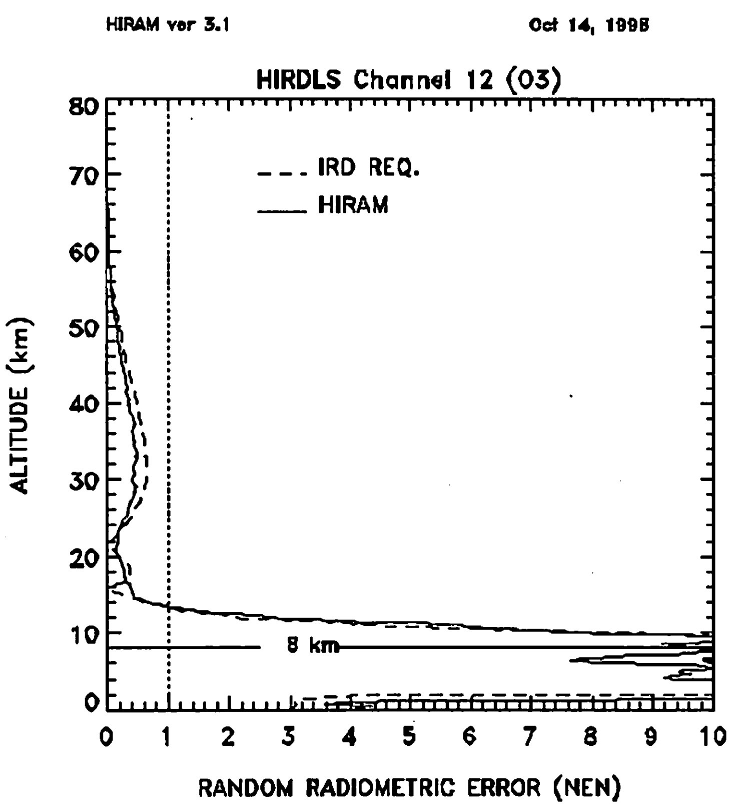


Figure 9b. Calculated radiometric jitter noise for HIRDLS channels 11 and 12 (solid line) based on the allowable LOS elevation angle PSD given in Figure 7. Jitter noise corresponding to the IRD requirement of 1 arcsec rms is shown by the dashed line.

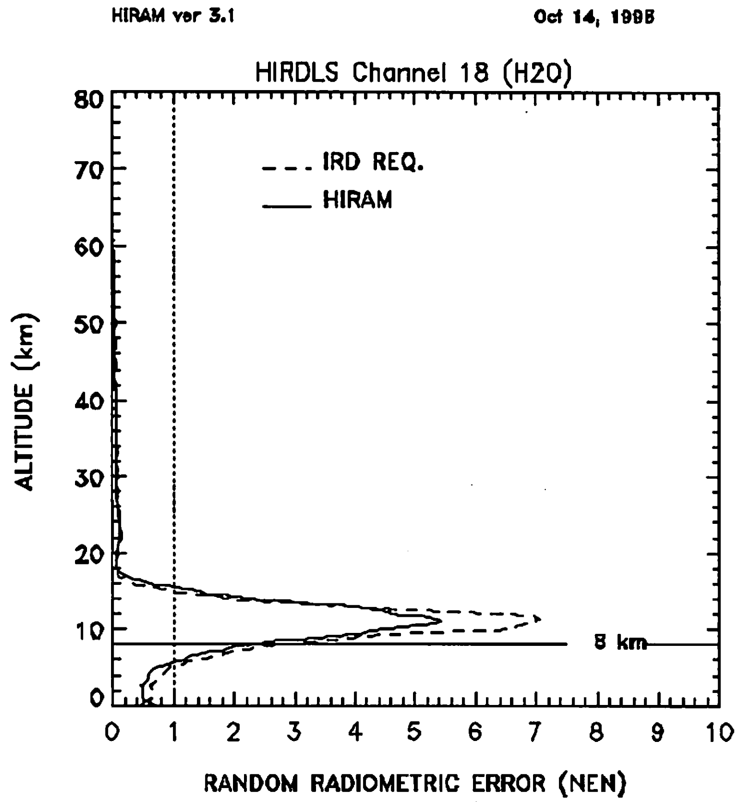


Figure 9c. Calculated radiometric jitter noise for HIRDLS channel 18 (solid line) based on the allowable LOS elevation angle PSD given in Figure 7. Jitter noise corresponding to the IRD requirement of 1 arcsec rms is shown by the dashed line.

Summary

The sensitivity of HIRDLS limb radiance measurements to unmeasured LOS jitter motions was investigated with special attention given to the effect of out-of-band jitter. Detailed calculations of out-of-band jitter noise using the HIRAM model show that moderate levels of out-of-band jitter, of the order of 5 arcsec rms, make a negligible contribution to the total radiometric error. As the amplitudes of the out-of-band jitter components become large, approaching 20 arcsec rms, harmonic frequencies of these jitter components are generated by the nonlinear altitude dependence of the radiance profile, some of which fall within the signal and chopper bands, and have sufficient amplitude to contribute significantly to jitter noise. Channels having rapidly changing vertical gradients in their radiance profiles, such as channels 8, 10, and 12, are especially sensitive to out-of-band jitter. These channels tend to be most affected near the bottom of their sounding ranges which is troublesome because this is in a region of keen scientific interest. The temperature sounding channels appear to be less sensitive to out-of-band jitter.

A new ITS-level LOS jitter requirement has been presented in terms of a power spectral density function. The advantage of stating the requirement in this way is that it provides a clear statement of the requirement and a clear means for comparing actual LOS jitter measurements against the requirement. The jitter PSD requirement, when combine with an assumed pointing error of 0.7 arcsec, results in random radiometric errors for each channel that are equal to or less than the radiometric error allowed by the IRD LOS uncertainty requirement. This has been shown to be the case for the four temperature sounding channels and several of the more stressing constituent channels. Over much of the altitude range, the radiometric error is dominated by the 0.7 arcsec rms pointing error with a much smaller contribution from the 0.2 arcsec rms in-band jitter, except at altitudes where the second derivatives of the radiance profiles show maxima. At these altitudes, the radiometric errors due to pointing and out-of-band jitter are of generally comparable magnitude. The systematic error resulting from the stated jitter PSD has not been carefully analyzed. There has been some preliminary analysis of synchronous jitter effects and it appears that the synchronous jitter requirement is met by the stated jitter PSD requirement with the addition of a stated LOS jitter measurement bandwidth of 0.1 Hz. This will be an area of further study.

The jitter PSD requirement presented in this TC sets a maximum level for LOS elevation angle jitter relative to inertial space that can be tolerated and still meet the science requirements. It has evolved during the analysis process from a preliminary version of the jitter PSD requirement which was overly constrained by fixing the final roll-off above 125 Hz to be -20 dB/decade. This preliminary jitter PSD set an out-of-band jitter level of 3" rms from 50 to 125 Hz . This was determined by the required jitter level near the chopping frequency, not by what level of out-of-band jitter could be tolerated. In that case, out-of-band jitter made a negligible contribution to jitter noise for all channels. As the analysis matured, this constraint was loosened. In addition, recent analyses by Alain Carrier at LOC showed that predicted out-of-band LOS jitter errors would be significantly greater than those allowed by the preliminary jitter PSD. The results of Alain's analysis was used to set the out-of-band jitter level such that it was just above the predicted level. At this level there is a significant contribution to jitter noise from the out-of-band components, particularly for channels 8, 10 and 12. Therefore, there is probably very little margin for increasing the out-of-band jitter level beyond what is reflected in the stated jitter PSD requirement without some impact to the science requirements on temperature and constituent retrieval precision.

Appendix I

Table A-1 gives the maximum radiance slope and where it occurs in altitude for each of the 21 channels. In addition, the table gives the radiometric jitter noise corresponding to 1 arcsec rms and 0.7 arcsec rms LOS angle uncertainties. The jitter noise is estimated by simply multiplying the maximum radiance slope by the equivalent rms pointing/jitter error at the tangent point†. The last column shows the noise equivalent angle (in arcsec) defined as the LOS jitter error that results in a radiometric jitter noise equal to 1 NEN. This is just a rehash of John Barnett's earlier calculation (see TC-OXF-89) with a change to the NEN requirement for channel 8. The Table gives a useful guide to the maximum expected jitter noise and where in the altitude range it will occur. As pointed out in TC-OXF-89, in all case except channel 4 and to some extent channel 3, the maximum gradient in the radiance profile occurs near the bottom of the required sounding range, due to the increasing limb path opacity with decreasing altitude. Table A-1 also provides a convenient check for the HIRAM calculations of jitter noise.

TABLE A-1. RANDOM RADIOMETRIC ERROR DUE TO LOS UNCERTAINTY

ch	NEN (Req.) W/m^2sr	Max. Radiance slope W/m^2sr/km	Altitude of max. slope** km	1 arcsec Max. Radiance error NEN	.7 arcsec Max. Radiance error NEN	NEA arcsec
1	1.20E-03	2.20E-01	10	2.66	1.86	3.76E-01
2	6.30E-04	4.80E-02	14	1.10	0.77	9.05E-01
3	5.90E-04	5.50E-02	30	1.35	0.95	7.40E-01
4	6.00E-04	8.30E-02	36	2.01	1.40	4.99E-01
5	4.30E-04	7.70E-02	39	2.60	1.82	3.85E-01
6	1.90E-04	1.20E-01	8	9.16	6.41	1.09E-01
7	2.00E-04	1.40E-01	8	10.15	7.11	9.85E-02
8*	4.20E-04	3.00E-01	8	10.36	7.25	9.66E-02
9	2.00E-04	1.30E-01	8	9.43	6.60	1.06E-01
10	1.50E-04	6.60E-02	8	6.38	4.47	1.57E-01
11	2.40E-04	6.50E-02	39	3.93	2.75	2.55E-01
12	9.60E-05	8.40E-02	8	12.69	8.88	7.88E-02
13	1.10E-04	8.30E-02	9	10.94	7.66	9.14E-02
14	1.10E-04	6.60E-02	9	8.70	6.09	1.15E-01
15	1.10E-04	2.10E-02	11	2.77	1.94	3.61E-01
16	1.10E-04	1.10E-02	11	1.45	1.02	6.90E-01
17	1.20E-04	4.50E-02	11	5.44	3.81	1.84E-01
18	1.20E-04	5.60E-02	11	6.77	4.74	1.48E-01
19	1.30E-04	2.00E-02	10	2.23	1.56	4.48E-01
20	1.60E-04	2.20E-02	15	1.99	1.40	5.02E-01
21	1.10E-04	1.30E-02	12	1.71	1.20	5.84E-01

* Note: ch. 8 NEN Req. reflects factor of 2 increase in NEN
** within IRD specified atmos. sounding range
† 1 arcsec = 14.5 m at the limb

For the purpose of analysis, the random tangent height uncertainty, *Δz(t)*, can be characterized in terms of its rms value integrated over some well defined frequency limit or bandwidth, defined by the final lowpass filter bandwidth. The total random radiometric error due to pointing error and jitter can be estimated using the following expressions,

$$\sigma^2_{\Delta N} = \sigma^2_{\Delta N_p} + \sigma^2_{\Delta N_{in}} + \sigma^2_{\Delta N_{ob}}$$

$$\sigma_{\Delta N_p} = R_t \left(\frac{\partial N}{\partial z}\right) \sigma_{\Delta \alpha_p} \quad , \quad \sigma_{\Delta N_{in}} = (c_o / c_1)\, R_t \left(\frac{\partial N}{\partial z}\right) \sigma_{\Delta \alpha_{in}} \quad ,$$

where $\sigma_{\Delta N}$ is the rms value of the radiometric jitter noise, $\sigma_{\Delta \alpha_p}$ is the rms residual pointing error in radians integrated over the signal band, $\sigma_{\Delta \alpha_{in}}$ is the rms in-band jitter error in radians integrated over 2 times the signal band centered about the chopping frequency, and $\sigma_{\Delta N_{ob}}$ is the rms radiometric error due to out-of-band jitter. The distance to the tangent point is R_t. The quantity (c_o / c_1) is the ratio of the average value of the chopping waveform to the fundamental component of the chopping waveform (e.g. (c_o / c_1) = 0.5/0.573) and it is just a consequence of the particular chopping waveform and the signal processing scheme. The errors are assumed to be are uncorrelated in this expression. Neglecting the contribution from OOB jitter, which is shown to be negligible for small OOB jitter levels (i.e. ≤ 5 arcsec rms), the rms radiometric jitter noise due to pointing and jitter errors can be readily calculated for any altitude if the radiance slope is known . The above expression gives us a first order understanding of the problem, including the altitude dependence and the magnitude of the jitter noise for given levels of uncorrected pointing and jitter errors.