VISSR ATMOSPHERIC SOUNDER

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I. Introduction

The Visible and Infrared Spin Scan Radiometer (VISSR) for the Synchronous Meteorological Satellites (SMS) is being modified to include the capability to make temperature and water vapor soundings of the atmosphere. The basic sounder concept and specifications were developed by the University of Wisconsin Space Science and Engineering Center under NASA contract NAS5-21607, and documented in a final report, SMS Sounder Specification, dated 30 April 1972. The present University of Wisconsin participation in the VISSR Atmospheric Sounder (VAS) Program, funded under NASA contract NAS5-21965, is directed at: (1) improving instrument specifications; (2) sounder design evaluation; (3) instrumentation testing; (4) calibration; and (5) data handling and processing.

Although the major U.W. effort will be in the area of data handling and processing, during the initial phases of the program improved instrument specification has received the most attention because of scheduling requirements. Specific topics of investigation are described in the following paragraphs.

II. Operating Modes

Discussions between University of Wisconsin and NOAA representatives have resulted in selection and definition of the following set of desirable modes of operation:

(1) OPERATIONAL SOUNDING
(2) MESOSCALE SOUNDING
(3) SOUNDING/IMAGING
(4) SPECIAL IMAGING

In the first two modes the VAS dwells on one latitude position to allow time averaging of samples for noise reduction (referred to DWELL SOUNDING) before stepping to the next latitude position. In the second two modes the VISSR scanner steps one latitude increment per spin. These and other characteristics are tabulated for comparison in Table 1.

III. Spectral Channels

Spectral channels presently under consideration are presented in Table 2 along with those specified in the original U.W. specification (SMS Sounder Specification, April 1972). Several significant differences can be noted. The total number of CO_2 channels in the 15μ absorption band has been reduced from eight to six. The new selections in this band were made on the basis of published optimization of M. Weinreb (Weinreb, 1972) and personal communication with W. L. Smith. The bandwidth reduction of the upper tropospheric channels (bands 2 and 3) were suggested by Smith to improve the sharpness of their respective weighting functions. Band 7 at 790 cm^{-1} was selected to replace the 1225 cm^{-1} channel of the old specification for sensing lower tropospheric water vapor. This change was made for two reasons: (1) the VISSR primary optics overcoated with SiO showed significant absorption near 1225 cm^{-1}; (2) W. L. Smith suggested that the 790 cm^{-1} would be better because of the possibility of methane contamination at 1225 cm^{-1}. At Smith's recommendation the 11μ window channel was shifted slightly and slightly reduced in bandwidth to make it cleaner (less affected by H_2O absorption). Band 12 is a window at 3.7μ for use in improving the reliability of clear column radiance retrievals. The nature of the improvement obtained and the processing techniques involved in obtaining it are documented in a paper by W. L. Smith (Smith, 1969) and verified by results of the ITPR experiment. Implementation of this channel, and channel 11 as well, is questionable because an increase in detector array complexity would be required. Channel 11 is a 4.3μ version of the Q branch at 15μ, i.e. its weighting function peaks well above the tropopause and could serve as a replacement for band 1. This appears to be

Table 1. Operating Mode Characteristics

	Box size at which NEN Req. met*	Latitude Stepping	Normal Spatial Coverage	Time to Sound Normal Coverage	Interruption of Full Frame Image Schedule
(1) OPERATIONAL SOUNDING	30 km	dwell for 100 spins, step 6 steps	30° latitude swath at SSP (485 IR lines)	1.5 min	yes
(2) MESOSCALE SOUNDING	11 km	dwell for 1000 spins, step 6 steps	45 km latitude swath at SSP (6 IR lines)	10 min	yes
(3) SOUNDING/IMAGING	300 km	one spin per step	full frame (1821 IR lines)	1.5 min (3 frames required to sequence through all channels)	no
(4) SPECIAL IMAGING	30 km	one spin per step	full frame (1821 IR lines)	N.A. (30 min to image)	no

* These are typical values; for channels which are insensitive to clouds larger box sizes are allowed (see performance section for details).

Table 2. VAS Spectral Channels

April 72 Spec.			Revised Spec.	
BAND CTR. (cm^{-1})	BAND PASS (cm^{-1})	BAND NO.	BAND CTR. (cm^{-1})	BANDPASS (cm^{-1})
669	5(8.1)	1	668.5	5(8.1)
680	20	2	686	10
690	20	3	698	16
700	20	4	715	20
715	20	5	745	20
735	20	6	760	20
745	20	7	790	20
760	20	8	895	140
875	150	9	1,380	40
1,225	60	10	1,490	150
1,380	60	11	2,345	75
1,490	150	12	2,683	450

very desirable because band 11 requires much less observation time than band 1 to reach required noise levels (see the section on performance).

IV. Autocovariance Calculations

Previous calculations of the autocovariance function, as reported in the April 72 final report on NAS5-21607, were based on assumptions of HgCdTe detector noise characteristics and an ideal bandpass presampling filter. Since we are currently evaluating performance characteristics of channels using InSb detectors, calculation of appropriate autocovariance functions is required. In addition, the ideal bandpass assumption produces unrealistic wiggles in the covariance function which affect the accuracy of noise estimates for averages of adjacent samples. Accomodating InSb detectors is simply accomplished by changing the 1/f of g.r. crossover frequency fc from 750 Hz (appropriate for HgCdTe) to 10 Hz. Removing the wiggles resulting from sharp filter cutoffs is described in the following.

The basic equation for caluclating the autocovariance function is

$$C(\tau) = \int_0^\infty P(f) \cos(2\pi f\tau)T(f)df$$

where we define: $P(f)$ = noise power spectral density $[(\text{erg/etc})^2/\text{Hz}]$
f = frequency (Hz)
τ = time interval (sec)
$T(f)$ = power transfer function of presampling filter

The basic form used for P(f) is: $P(f) = K(1 + \frac{f_c}{f})$, where

f_c = cutoff frequency (Hz)
K = frequency independent parameter determined by detector type, size, and operating conditions

In previous calculations the power transfer function was assumed to have the form $T(f) \approx \begin{cases} 0 \text{ for } f < f_1 \text{ or } f > f_2 \\ 1 \text{ for } f_1 \leq f \leq f_2 \end{cases}$

i.e. an ideal bandpass function with f_1 and f_2 the upper and lower cutoff frequencies respectively. The corresponding expression for $C(\tau)$ became, in this case, $C(\tau) = \int_{f_1}^{f_2} P(f) \cos 2\pi f\tau df$, and efficient software was generated to calculated.

In order to deal with the power transfer function more exactly, and still use the same software, we used the approximation

$$T(f) = \sum_{k=1}^{N} w_k T_k(f)$$, where N = 6 in current calculations and we define

$$T_k(f) = \begin{cases} 0 \text{ for } f < f_{1,k} \text{ or } f > f_{2,k} \\ 1 \text{ for } f_{1,k} \le f \le f_{2,k} \end{cases}$$

and w_k, $f_{1,k}$, $f_{2,k}$ are chosen to best approximate T(f), the normal relationship between w_k and $f_{1,k}$, $f_{2,k}$ being

$$w_1 = 1 - T(\tfrac{1}{2}[f_{2,1} + f_{2,2}])$$

$$w_k = T(\tfrac{1}{2}[f_{2,k} + f_{2,k-1}]) - T(\tfrac{1}{2}[f_{2,k} + f_{2,k+1}])$$

$$w_N = T(\tfrac{1}{2}[f_{2,N} + f_{2,N-1}])$$

$$T(f_{1,k}) = T(f_{2,k}).$$

The approximate and exact curves for T(f) are plotted near the upper cutoff in Figure 1.

The calculation of $C(\tau)$ then requires evaluation of the expression

$$C(\tau) = K \sum_{k=1}^{N} w_k \int_{f_{1,k}}^{f_{2,k}} (1 + \frac{f_c}{f}) \cos 2\pi f\tau df$$

and the normalized autocovariance function becomes

$$\frac{C(\tau)}{\sigma^2} = \frac{\sum_{k=1}^{N} w_k \int_{f_{1,k}}^{f_{2,k}} (1 + \frac{f_c}{f}) \cos 2\pi f\tau df}{\sum_{k=1}^{N} w_k [f_{2,k} - f_{1,k} + f_c \ln \frac{f_{2,k}}{f_{1,k}}]}$$

Figure 2 displays $C(\tau)/\sigma^2$ for both f_c = 750 Hz (appropriate to HgCdTe) and f_c = 10 Hz (appropriate to InSb).

Using these new autocovariance functions it is then possible to determine the noise characteristics of the mean over an area. The ratio of the standard deviation of the mean to the RMS noise of a single sample is

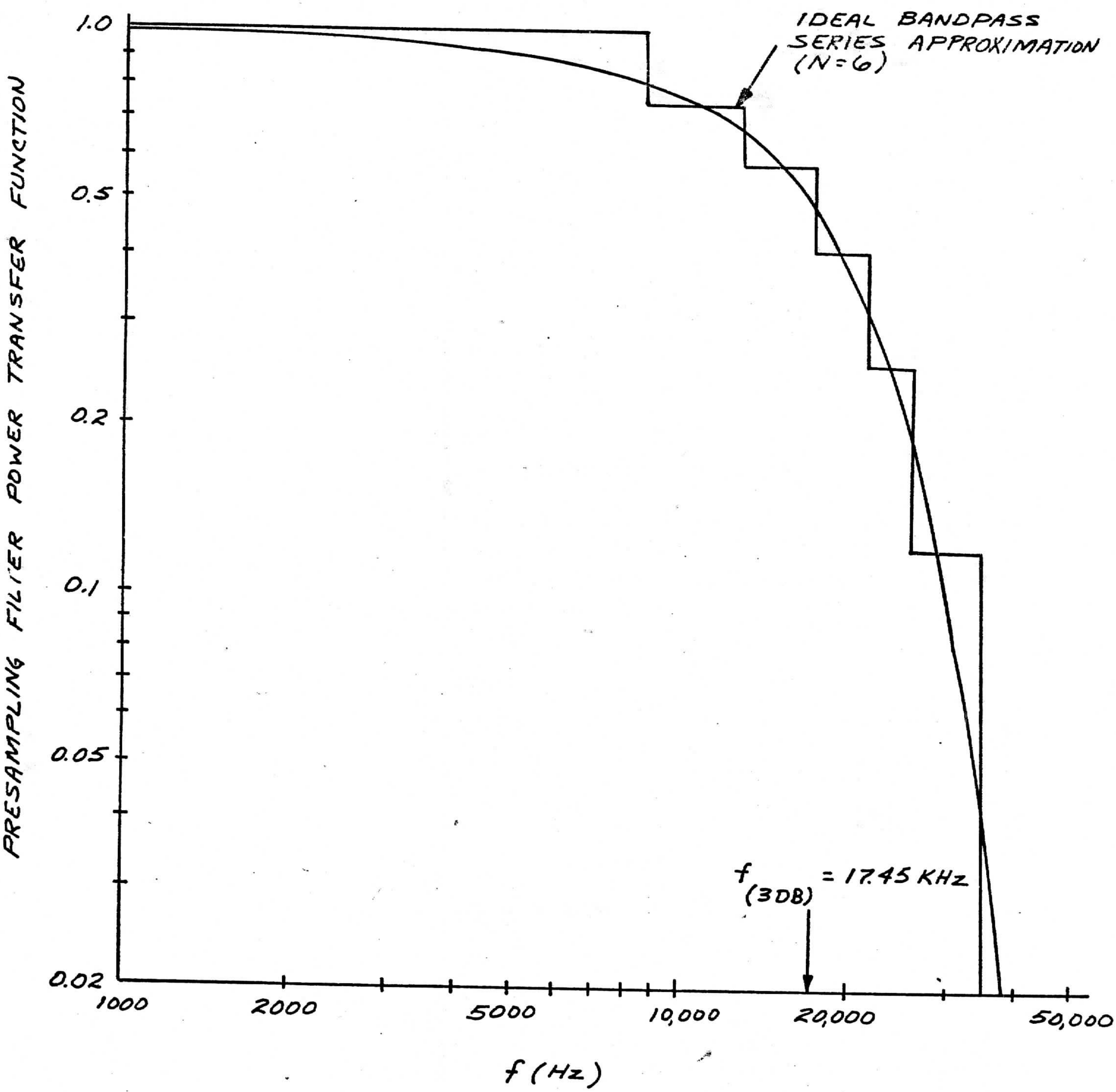

Figure 1 Exact and Approximate Form of T(f)

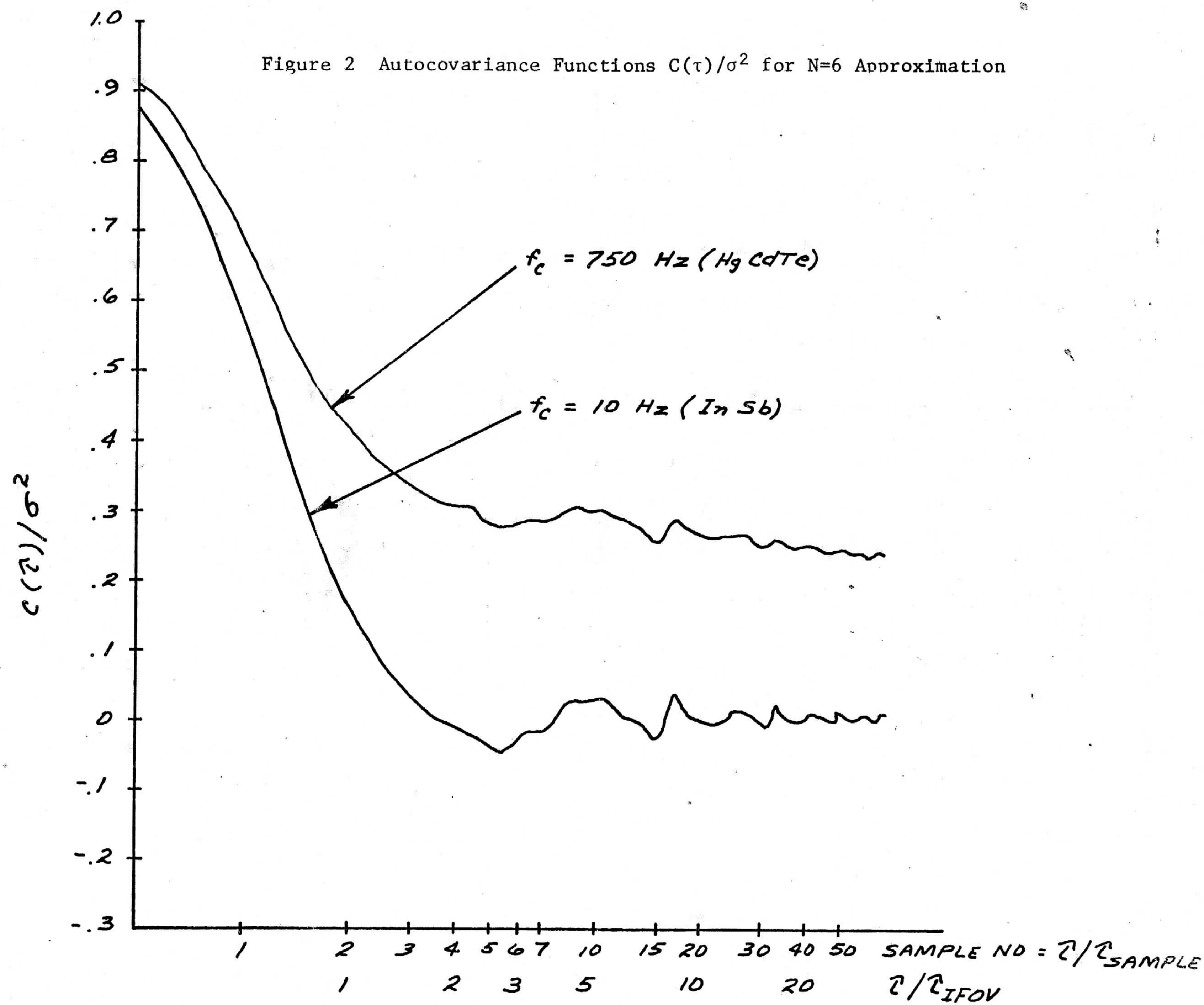

Figure 2 Autocovariance Functions $C(\tau)/\sigma^2$ for N=6 Approximation

displayed in Figure 3 as a function of the linear dimension of the square over which the mean is taken (integrating square). Parenthetical numbers in this figure indicate the corresponding number of lines and number of samples per line used in the average.

V. Performance Estimates and Spin Requirements

The single sample noise equivalent radiance (NEN) is determined from instrument parameters through the equation

$$NEN = \frac{\gamma[A_d \Delta f_N]^{1/2}}{A_o \alpha^2 D^* \rho_\lambda \Delta\nu}$$

which makes use of the following notation:

γ = amplifier noise factor

A_d = detector area (cm^2)

Δf_N = effective noise bandwidth (Hz)

A_o = effective collecting aperture of optics (cm^2)

α = angular resolution (radians)

D^* = specific detectivity ($cmHz^{1/2}/w$)

ρ_λ = net transmission of optics and filters

$\Delta\nu$ = spectral bandwidth (cm^{-1}).

Among these parameters the following are taken as constant for all spectral channels: $\gamma = 1.05$, $\sqrt{A_d} = .125$ mm, $A_o = 1090$ cm^2, and $\alpha = 0.3$ mr. The parameters which vary as a function of spectral channel and resulting NEN values are presented in Table 3.

Since accuracy requirements are stated for spatial resolutions larger than the detector FOV in many cases, the autocovariance function is needed to determine the equivalent NEN for appropriate spatial averages. The results of this determination are presented in Table 4 relative to NEN values for single samples.

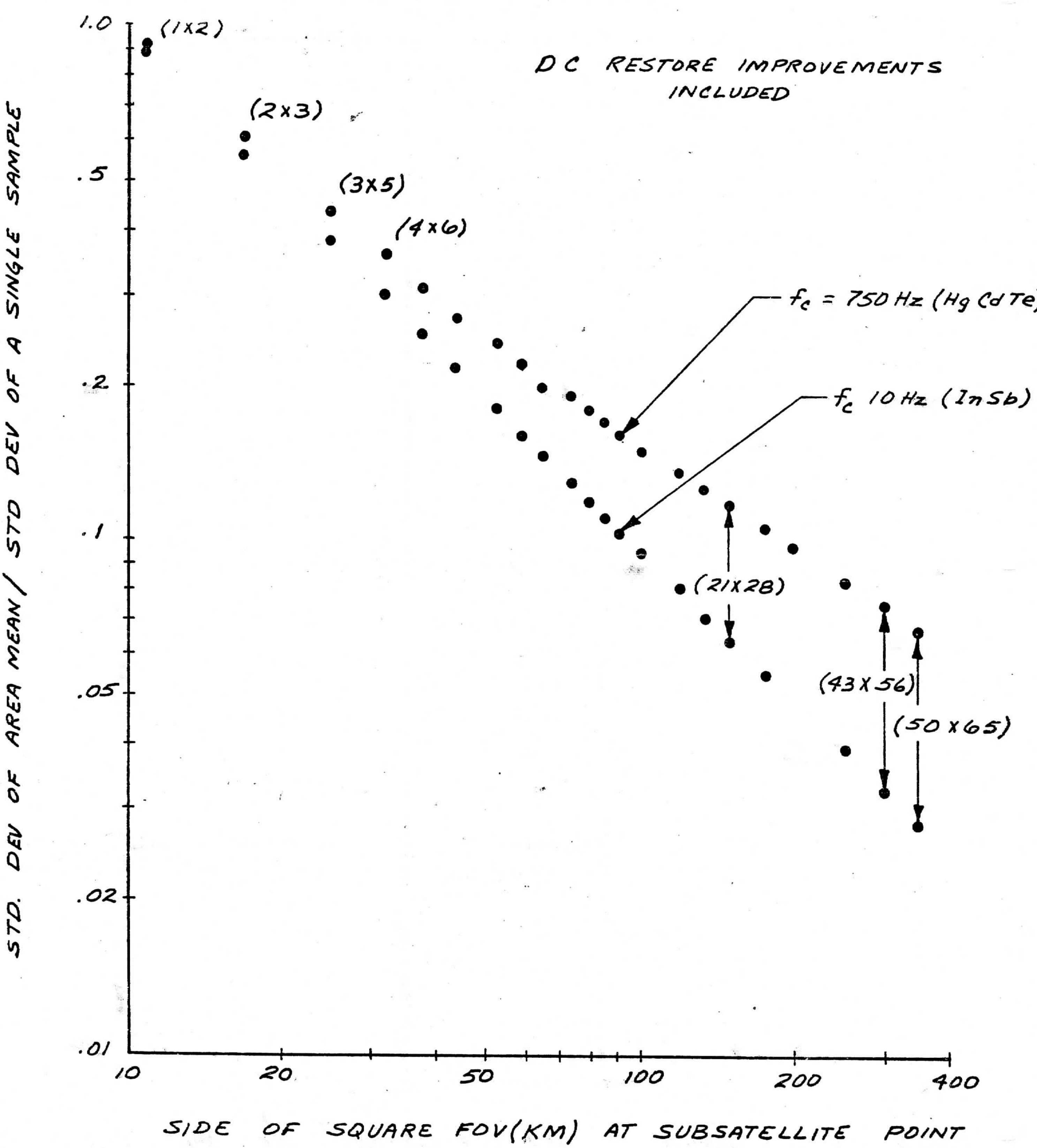

Figure 3 RMS Noise as a Function of Size of the Integrating Square

Table 3. Single Sample NEN Values

	Band	$\nu(cm^{-1})$	$\Delta\nu(cm^{-1})$	ρ_λ (1)	$D^*(cmHz^{1/2}/N)$	Δf_N(KHz)	NEN(erg/$[cm^2$-sec-ster-$cm^{-1}]$)
	1	668.5	5(8.1)	0.124	1.69×10^{10}	24.75	12.40
	2	686	10	0.211	1.85	24.75	5.39
	3	698	16	0.282	1.92	24.75	2.43
	4	715	20	0.321	1.97	24.75	1.66
	5	745	20	0.321	1.88	24.75	1.74
	6	760	20	0.321	1.82	24.75	1.80
	7	790	20	0.321	1.75	24.75	1.87
	8	895	140	0.380	1.69	24.75	.234
	9	1380	40	0.438	0.77	24.75	1.56
	10	1490	150	0.438	0.70	24.75	.458
(2)	11	2345	75	0.246	32.0	18.5	0.031
(2)	12	2683	450	0.308	28.0	18.5	0.0047
(3)	12a	2683	450	0.410	48.0	18.5	0.0021

(1) Transmission Values based on SBRC estimates for relay optics design option No. 4 - offset hybrid (VISSR Sounder Program Review, 11 Sept. 73)

(2) 3.44 to 4.50 μm shielding of InSb Detector

(3) 3.44 to 4.06 μm shielding of InSb Detector

Table 4. Relative NEN as a Function of Effective Resolution

LINES X SAMPLES AVERAGED	RESOLUTION AT SUBSAT. PT. (Km x Km)	NEN (HgCdTe)	NEN (InSb)
1 x 1	10.7 x 10.7	1.00	1.00
1 x 2	10.7 x 10.7	.913	.889
4 x 6	31.4 x 32.2	.359	.303
21 x 28	148.2 x 150.4	.117	.064
43 x 56	299.4 x 300.7	.075	.033

From the results of Table 3 and Table 4 it is possible to determine performance characteristics for each of the operating modes discussed previously.

The spins per band required for the operational sounding mode are presented in Table 5. However, not all bands would be used in the final system. Net performance in this mode is determined for three different band selections: (1) b nds 1-10; (2) bands 1-10 and band 12a; and (3) bands 2-12. Total spins/dwell and sounding rates are presented in Table 6 for each case. Note that the (3) option omits the Q-branch channel at 668.5 cm^{-1} in favor of the 4.3μ band at 2345 cm^{-1}. This yields a better than 30% reduction in sounding time, under the assumed conditions.

Spin requirem nts for the mesoscale sounding mode of operation are presented in Table 7.

The total spins per dwell and sounding rates for each of the three band selections are presented in Table 8. Again note the improved efficiency of the 2-12 selection (in this case a 40% reduction in time over the other two selections).

Table 5. Spin Requirements for Operational Sounding
(NEN units are erg/[sec-cm^2-ster-cm^{-1}])

Band	NEN/sample	Req NEN @ Res	Effective NEN @ Res	Req Spins/Band
1	12.4	.25 @ 150 km	1.45	34
2	5.39	.25 @ 150 km	0.63	7
3	2.43	.25 @ 30 km	0.87	12
4	1.66	.25 @ 30 km	0.60	6
5	1.74	.25 @ 30 km	0.62	6
6	1.80	.25 @ 30 km	0.65	7
7	1.87	.25 @ 30 km	0.67	7
8	.234	.25 @ 30 km	0.084	1
9	1.56	.15 @ 30 km	0.56	14
10	0.458	.10 @ 30 km	0.164	3
11	0.031	.002 @ 150 km	0.0019	1
12	0.0047	.002 @ 30 km	0.0014	1
12a	0.0021	.002 @ 30 km	0.0006	1

Table 6. Net Performance in Operational Sounding Mode

Band Selection	Required Total Spins/Dwell	Time per(1) 6 Line Swath	Time per 30° Swath (485 lines)
1-10	97	58 sec	78.4 min (1.30 hr)
1-10,12a	98	59 sec	79.2 min (1.32 hr)
2-12	65	39 sec	52.6 min (.87 hr)

(1) Bands 1-10 are sensed by means of a 6-element HgCdTe array spanning 6 latitude steps (one/element); bands 11, 12 or 12a are sensed by means of a similar array of InSb detectors.

Table 7. Spin Requirements for Mesoscale Sounding

Band	Req NEN @ Res	Effective NEN @ Res	Required Spins/Band
1	.25 @ 30 km	4.45	317
2	.25 @ 30 km	1.94	60
3	.25 @ 11 km	2.21	78
4	.25 @ 11 km	1.51	36
5	.25 @ 11 km	1.58	40
6	.25 @ 11 km	1.64	43
7	.25 @ 11 km	1.70	46
8	.25 @ 11 km	.213	1
9	.15 @ 11 km	1.42	90
10	.10 @ 11 km	.418	18
11	.002 @ 30 km	.0094	22
12	.002 @ 11 km	.0042	4
12a	.002 @ 11 km	.0019	1

Table 8. Net Performance in Mesoscale Mode

Band Selection	Required Total Spins/Dwell	Dwell Time/ 6 Line Swath	Rate of Coverage (km of lat./hr)
1-10	729	7.29 min	340 km/hr
1-10,12a	730	7.30 min	340 km/hr
2-12	438	4.38 min	565 km/hr

In the imaging/sounding mode the VISSR is stepped one latitude step/spin. As a result only complete spatial coverage can be achieved in only 6 spectral channels per frame (or reduced amplitude frame) in one pass. Since in each frame one of the six channels must be the 11μ IR window channel, only five sounding channels per pass can be sampled. Other restrictions depend on the band selection implemented. Detailed filter sequences for each of the three band selections are presented in Table 9. Note that selections including InSb capabilities, i.e. at least the 3.7μ window channel 12 or 12a, repeat both 11.1μ and 3.7μ channels (8 and 12 or 12a) on every frame.

Radiometric performance for the sounding/imaging mode is summarized by Table 10. Note that for the first two band selections (those containing band 1) the NEN requirement for band 1 is met after two frame sequences (6 frames or 3 hours in the first case and 8 frames or 4 hours in the second case).

The special imaging mode is similar to the imaging/sounding mode except that only window channels and the 6.7μ water vapor band are sampled in the sequence. In this way it is possible to obtain useful images in the 6.7μ band by repeated observations. The two filter step sequences (with and without band 12 or 12a) are presented in Table 11.

Since the difference between $\sqrt{4}$ and $\sqrt{5}$ is fairly small only the sequence with InSb will be considered in the calculation of radiometric performance. A summary of the water vapor accuracy in the special imaging mode is presented in Table 12.

Table 9. Filter Sequences for Imaging/Sounding

Band Selection	Frame 1	Frame 2	Frame 3	Frame 4
1-10	8	8	8	
	2	6	1	
	2	7	1	
	3	9	1	
	4	9	1	
	5	10	1	
	←Basic Sequence Time = 1.5 hrs→			
1-10,12a	8	8	8	8
	12a	12a	12a	12a
	2	5	9	1
	2	6	9	1
	3	7	9	1
	4	10	1	1
	←Basic Sequence Time = 2.0 hrs→			
2-12	8	8	8	
	12	12	12	
	2	5	9	
	2	6	9	
	3	7	11	
	4	10	11	
	←Basic Sequence Time = 1.5 hrs→			

Table 10. Radiometric Performance in the Imaging/Sounding Mode

Band	Req NEN @ Res	NEN(2) Obtained @ Res: Bands 1-10 3 Frames	Bands 1-10,12a 4 Frames	Bands 2-12 3 Frames
1	.25 @ 400 km	.34	.31	N.A.
2	.25 @ 400 km	.24	.24	.24
3	.25 @ 200 km	.23	.23	.23
4	.25 @ 200 km	.16	.16	.16
5	.25 @ 200 km	.16	.16	.16
6	.25 @ 200 km	.17	.17	.17
7	.25 @ 200 km	.18	.18	.18
(1) 8	.25 @ 11 km	-----------------	.23 each frame	-----
9	.15 @ 200 km	.11	.11	.11
10	.10 @ 200 km	.04	.04	.04
11	.002 @ 400 km	N.A.	N.A.	.001
(1) 12	.002 @ 30 km	N.A.	N.A.	.002 each frame
(1) 12a	.002 @ 11 km	N.A.	.002 each frame	N.A.

(1) Requirements for window channels are more severe because they are used for cloud discrimination and imaging.

(2) NEN Units are erg/(cm^2-sec-ster-cm^{-1})

Table 11. Filter Step Sequences for Water Vapor Imaging

Relative Latitude Step	w/o InSb Filter Position	w/o InSb Band Center (cm^{-1})	with InSb Filter Position	with InSb Band Center (cm^{-1})
1	8	895	8	895
2	10	1490	12	2683
3	10	1490	10	1490
4	10	1490	10	1490
5	10	1490	10	1490
6	10	1490	10	1490

Table 12. Performance Estimates for Water Vapor Imaging

	Image Spatial Resolution (lines x samples)	
	10.7 km (1 x 2)	32 km (4 x 6)
NEN	0.209	0.082
NEΔT @ 200°K	4.5°K	1.8°K
NEΔT @ 220°K	2.1°K	0.8°K
NEΔT @ 240°K	1.1°K	0.4°K
NEΔT @ 260°K	0.6°K	0.3°K

VI. References

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