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HIGH RESOLUTION DYNAMICS LIMB SOUNDER

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Limitations on Satellite Radiometry

I want to ask the question:

What limits the accuracy of in-flight radiometry, without considering the effects of FOV, pointing and spectral bandpass except insofar as they have a direct *radiometric* effect.

Start from the basic telemetry equation for a filter radiometer:

$$N = C + G \int d\Omega_{\mathbf{n}}\, d^2\mathbf{x}\, d\bar{\nu}\, F(\mathbf{n}, \mathbf{x}, \bar{\nu})\, R(\mathbf{x}, \mathbf{n}, \bar{\nu}) \tag{1}$$

where

N Output count

C Offset count, with contributions from electronic offsets and radiometric offsets, such as emission from telescope mirrors

R Radiance at the entrance pupil of the radiometer:

- $\mathbf{x}$ gives the location in entrance pupil
- $\mathbf{n}$ gives the direction at the entrance pupil
- $\bar{\nu}$ wavenumber

F Optics transmission function

G Electronics gain

We can move constant factors between F and G so we define $F_{max} = 1$.

This looks very general, but it isn't:

Assumptions:

Overall Linearity

Spatial Additivity (effects of radiance on different parts of the detector just add)

The function F may have non-trivial dependence on instrument parameters *e.g.* FOV on chopper and phasing.

The calibration task is then:

Measure C as a function of time

Measure G as a function of time

Know F from pre-flight calibration

Zeroth Approx to In-flight Calibration

Normally assume that the function F factorises so that

$$F(\mathbf{n}, \mathbf{x}, \bar{\nu}) = F_{FOV}(\mathbf{n}) F_{Pupil}(\mathbf{x}) F_{\bar{\nu}}(\bar{\nu})$$

where each factor is normalized to 1 maximum. Each factor can be integrated to define the basic instrument parameters:

$$\begin{aligned} \text{Aperture} \quad A &= \int d^2\mathbf{x}\, F_{Pupil}(\mathbf{x}) \\ \text{Field} \quad \Omega_{FOV} &= \int d\Omega_{\mathbf{n}}\, F_{FOV}(\mathbf{n}) \\ \text{Bandwidth} \quad \Delta\bar{\nu} &= \int d\bar{\nu}\, F_{\bar{\nu}}(\bar{\nu}) \\ \text{Mean } \bar{\nu} \quad \bar{\nu}_0 &= \int d\bar{\nu}\, \bar{\nu} F_{\bar{\nu}}(\bar{\nu}) \end{aligned} \tag{2}$$

Further assume that the atmospheric radiance is uniform over the entrance aperture. (This has to be the most accurate assumption in the paper!) Then (1) becomes

$$N = C + GA \int d\Omega_{\mathbf{n}}\, d\bar{\nu}\, F_{FOV}(\mathbf{n}) F_{\bar{\nu}}(\bar{\nu})\, R(\mathbf{n}, \bar{\nu}) \tag{3}$$

Then our two-point calibration requires just:
- a Space View $R_S = 0$
- a Calibration View $R_C = B(\bar{\nu}, T)$

where each radiance is uniform over the aperture and the FOV. Using the corresponding telemetry counts N we form the ratio

$$\frac{N - N_S}{N_C - N_S} = \frac{\int d\Omega_{\mathbf{n}}\, d\bar{\nu}\, F_{FOV}(\mathbf{n}) F_{\bar{\nu}}(\bar{\nu})\, R(\mathbf{n}, \bar{\nu})}{\Omega_{FOV} \int d\bar{\nu}\, F_{\bar{\nu}}(\bar{\nu})\, B(\bar{\nu}, T)} \tag{4}$$

which gives the filtered radiance averaged over the FOV in terms of a black body radiance at temperature T. Finally we can multiply by a theoretical ratio of black body filtered radiances to express the radiance in terms of a standard temperature T_0:

$$\text{Radiance} = \frac{N - N_S}{N_C - N_S} \frac{\int d\bar{\nu}\, F_{\bar{\nu}}(\bar{\nu})\, B(\bar{\nu}, T)}{\int d\bar{\nu}\, F_{\bar{\nu}}(\bar{\nu})\, B(\bar{\nu}, T_0)} \tag{5}$$

For the purposes of error analysis we can approximate the filtered radiances:

$$\int d\bar{\nu}\, F_{\bar{\nu}}(\bar{\nu})\, B(\bar{\nu}, T) = B(\bar{\nu}_0, T) \Delta\bar{\nu}$$

This gives us just two error sources from our Zeroth Approximation,one of which only appears if the actual black body is not at the standard T_0.

Source	**Fractional Sensitivity**	**Typical Size**
Thermometry	$\frac{\partial}{\partial T} \ln B(\bar{\nu}, T)$	1%/K @ 17.4μm 3%/K @ 6.2μm
Spectral Cal	$(T - T_0)\, \frac{\partial^2 \ln B}{\partial T \partial \bar{\nu}}$	$\sim$ 0.02%/cm^{-1}

First Approx to In-flight Calibration

Of course this ignores all the real problems! The most obvious are

a) Imperfect calibration view.

Viewing the black body (emissivity $\epsilon \approx 1$) through one auxiliary mirror (emissivity $\epsilon_m \approx 0$)

$$\begin{aligned} R_C &= \epsilon(1-\epsilon_m)B(T) + \epsilon_m B(T_m) + (1-\epsilon)(1-\epsilon_m)B(T_e) \\ &= B(T) + \alpha_m\left(B(T_m) - B(T)\right) + \alpha_e\left(B(T_e) - B(T)\right) \end{aligned}$$

where $B(T_e)$ is a representation of the radiance *into* the black body. The mirror term is not a serious problem, if T_m can be controlled, or at least measured. The environment term *is* a serious problem, because it depends on the whole radiance entering the black body which is probably incapable of being modelled, and varies on timescales from orbit to lifetime. A reasonable fractional upper limit at 6.4μm might be $(1-\epsilon)$ or about 0.2%, less at longer wavelengths.

b) Optics transmission function does not factorize.

Modifies above equations, but new problems are not *mainly* radiometric. General problem of measuring the correct averages over $F(\mathbf{n}, \mathbf{x}, \bar{\nu})$. In (5), the spectral function required is

$$F_{\bar{\nu}} = \int d\Omega_{\mathbf{n}}\, d^2\mathbf{x}\, F(\mathbf{n}, \mathbf{x}, \bar{\nu})$$

which requires test beam to fill aperture A and field Ω_{FOV}. Easily a larger error than the Spectral Cal above.

c) Calibration View does not fill $A\Omega_{FOV}$

Basically a stray light problem. Need a realistic instrument FOV including scattered light, and consider effect of auxiliary mirror.

All these affect measurement of G; hence scale with radiance; hence our First Approximation error budget suggests 0.5% radometry is no problem.

Source	**Typical Size**	**Comment**
Thermometry	0.05% @ 17.4μm 0.15% @ 6.2μm	For 50 mK error
Spectral Cal	0.1%??	Includes error in $F_{\bar{\nu}}$
Emissivity	0.05% @ 17.4μm 0.2% @ 6.2μm	Depends on radiance into black body
Underfull $A\Omega$	0.1%?	Depends on optics quality and contamination

Second Approx to In-flight Calibration

The worst is yet to come! Errors in G not so serious as errors in C at small radiances. These arise if C varies with scan angle, so is not cancelled by $N - N_S$: *scan-dependent stray.*

- probably a stray light problem
- related problem of earthshine for limb viewers (not strictly a radiometric problem)
- measure in orbit (involves spacecraft manoeuvre - anathema to project!)
- error in correction is *radiance* error not scale factor.