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Development of Response Models for the Earth Radiation Budget Experiment (ERBE) Sensors:

Part IV – Preliminary Nonscanner Models and Count Conversion Algorithms

(NASA-CR-178295) DEVELOPMENT OF RESPONSE MODELS FOR THE EARTH RADIATION BUDGET EXPERIMENT (ERBE) SENSORS. PART 4: PRELIMINARY NONSCANNER MODELS AND COUNT CONVERSION (Information and Control Systems) N88-10317 Unclas G3/35 0104546

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FOREWORD

This report entitled "Development of Response Models for the Earth Radiation Budget Experiment (ERBE) Sensors" consists of the following four parts.

Part I, NASA CR-178292, is entitled "Dynamic Models and Computer Simulations for the ERBE Nonscanner, Scanner and Solar Monitor Sensors".

Part II, NASA CR-178293, is entitled "Analysis of the ERBE Integrating Sphere Ground Calibration".

Part III, NASA CR-178294, is entitled "ERBE Scanner Measurement Accuracy Analysis Due to Reduced Housekeeping Data".

This is Part IV, NASA CR-178295, entitled "Preliminary Nonscanner Models and Count Conversion Algorithms".

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LIST OF SYMBOLS

Symbols	Name
A_k	Area of k-element surface having Radiant interchange
A_{k-i}	Contacting Area between k and i elements
A_{ki}	Elements of A Matrix (Variable 7)
B_i	Elements of B Vector (Variable 10 of the nonscanner sensor model)
B_{Qi}	Elements of B_Q Vector (Variable 9)
b	Constant of Equations (8) and (9)
C_k	Specific heat Capacity of k-element
$\bar{C}_T$	Conversion Coefficient Matrix (see Equations (8) and (9))
$\bar{C}_b$	Constants due K_1 and K_2 (see Equations (8) and (9))
D_{ki}	Elements of D Matrix (Variable 8)
$E_{FOV(t)}$	Irradiance at FOV from Target Source
F_{j-i}	View Factors between j and i surfaces
$F_{j-i(K-L)}$	View Factor between j and the image of i by intervening specular surface K through L.
f(T,E)	Steady State function (see Equation 13)
G	Equation (5) (Variable 3 & 4) (For the sensor without filter dome)
$\bar{G}$	Equation (4) (Variable 3 & 4) (For the sensor with filter dome)
H_{kji}	Equation (3) (Variable 2)
h_{k-i}	Contacting Thermal Conductance of elements k & i

LIST OF SYMBOLS (CONTINUED)

Symbols	Name
K_1, K_2 & K_3	Constants in Thermal control Feedback
k_k	Thermal Conductivity of k-element
L_{k-i}	Shortest distance between the center of weight of k-element and the contacting point of k-element to its neighboring i-element
M_k	Equation (6) (Variable 5)
N	Electronic noise
P_{j-i}	Equation (2) (Variable 1)
$\dot{Q}_k$	Heat generation of heater k
R_{ki}	Thermal Resistance between k and i elements, Equation (7) (Variable 6)
T_k	Temperature of k-element
V_k	Volume of k-element
V	Counts

Greek Letter	Name
γ_k	Density of k-element
γ_{oi}	Column matrix (see Equation (12))
ϵ_k	Emissivity of k-surface
ε_{j-i}	Exchange Factors between j and i specular surfaces, Equation (1)
ρ_k	Reflectivity of k-surface
τ_k	Transmissivity of k-transparent surface
σ	Boltzmann constant

Superscripts	Name
d	Diffuse
s	Specular

Subscripts	Name
B	Base
F	Field-of-View
H	Heat Sink
i	Vector component or element i
k	Element, surface or sampling instant k
L,l	Longwave
m	Index of rounded value
o	Initial value
oi	Table look-up value for vector component i
S,s	Shortwave
T,t	Total (wavelength)

Subscripts of number subscripts (see Figure 7)	
1_a	Surface 1 facing enclosure a
1_c	Surface 1 facing enclosure c
1_e	Surface 1 facing enclosure e
2_e	Surface 2 facing enclosure e
3_d	Surface 3 facing enclosure d

Subscripts of number subscripts (see Figure 7)

3_e	Surface 3 facing enclosure e
3_f	Surface 3 facing enclosure f
4_c	Surface 4 facing enclosure c
5_b	Surface 5 facing enclosure b
6_b	Surface 6 facing enclosure b
7_d	Surface 7 facing enclosure d
7_t	Surface 7 facing enclosure t
8_b	Bottom surface of 8 seeing cavity 1
8_t	Top surface of 8 seeing filter dome or cavity b
9_a	Surface 9 facing enclosure a
9_b	Surface 9 facing enclosure b

Enclosure a (see Figure 8)

$j = 1, 8_b, 8_t, 9_a$ (with filter dome)

$j = 1, 8_b, 9_a$ (without filter dome)

Enclosure b (see Figure 8)

$j = 5, 6, 9_b, 10$ (with filter dome)

$j = 5, 6, 8_t, 9_b, 10$ (without filter dome)

LIST OF ACRONYMS

Acronym	Definition
ACR	Active Cavity Radiometer
FOV	Field-of-View
LW	Longwave
MFOV	Medium Field-of-View
MKF	Modified Kalman Filtering (algorithm)
NS	Nonscanner
NOM	Nominal
SSL	Steady-state linearization (algorithm)
SW	Shortwave
WFOV	Wide Field-of-View

1. INTRODUCTION

This report entitled "Development of Response Models for the Earth Radiation Budget Experiment (ERBE) Sensors" consists of four parts. This part, Part IV, NASA CR-178295, is entitled "Preliminary Nonscanner Models and Count Conversion Algorithms".

The remaining parts are as follows.

Part I, NASA CR-178292, is entitled "Dynamic Models and Computer Simulations for the ERBE Nonscanner, Scanner and Solar Monitor Sensors".

Part II, NASA CR178293, is entitled "Analysis of the ERBE Integrating Sphere Ground Calibration".

Part III, NASA CR-178294, is entitled "ERBE Scanner Measurement Accuracy Analysis Due to Reduced Housekeeping Data".

This document discusses in greater detail the preliminary nonscanner models introduced in Part I of this report. The mathematical modeling equations and count conversion algorithms are discussed in greater depth. The purpose of this document is therefore to define two count conversion algorithms and the associated dynamic sensor model for the M/WFOV nonscanner radiometers. The model is required to provide and update the constants necessary for the conversion algorithms, though the frequency with which these updates needed to occur was uncertain. Since the count conversion equations themselves are functions of the sensor temperatures and impinging radiation in which these temperatures are transmitted together with the sensor radiometric data, other parameters updated from the senosr model were suggested to be as infrequent as once per month after instrument performance had been validated. The final selection of an algorithm and its associated sensor model was dependent on the completion of (1) sensor characterization and calibrations and (2) computational simulation and analyses of various measurements and data reduction processes.

2. NARRATIVE DESCRIPTION

2.1 Approach - The following approach was pursued: (1) To develop a mathematical model of the sensors which accounts for the conversion of irradiance (W/m^2) at the sensor FOV limiter to data (counts). (2) To derive from this model two algorithms for the conversion of data (counts) to irradiance (W/m^2) at the sensor FOV aperture. (3) To develop measurement models (which account for a specific source together with the sensor) for the

(a) sensor characterization and calibration, in order to empirically determine constants in the sensor model and conversion algorithm;

(b) pre/post launch calibration, in order to check and update (if necessary) constants in the sensor model; and

(c) inflight measurements, in order to properly apply constants to the conversion algorithm.

Of the two algorithms, one is of the gain/offset type that would be preferred because of its computational simplicity provided that it is sufficiently accurate. The other algorithm is of the Kalman filter type that may otherwise be required. The mathematical models of the sensors and count conversion algorithms are presented in this document.

2.2 Sensor Models - The nonscanner sensors are active cavity radiometers with medium and wide field-of-view (M/WFOV) limiters and shortwave (SW) and total (T) responses (see, e.g. Fig. 1). The SW response is obtained by the inclusion of a fused silica dome filter over the cavity aperture. The dynamic model for the T sensors has 8 themal nodes and for the SW sensors has one additional node for the filter. In addition, the model accounts for the active electrical heater (H) and three temperature probes (P) as well as for the signal amplification and analog-to-digital conversion.

Irradiance inputs, which are treated as another thermal node, are partially incident directly on the cavity aperture (node 8), partially absorbed and reflected by the base (5) and FOV limiter (6), and for the SW sensor also absorbed, reflected, and transmitted by the filter (9). The absorbed irradiance raises the temperature of nodes 5, 6, and 9 and causes unwanted thermal radiation toward the cavity (1) and heat conduction through nodes 4, 5, 6, 8 and 9 to the cavity (1) and heat sink (2). Some of the reflected irradiance from nodes 5, 6 and 9 may scatter into the cavity (1). The unwanted as well as source irradiance that is absorbed by the cavity walls increases its temperature. The electrical resistance temperature probe wound around the cavity walls senses this temperature change and activates an electrical feedback circuit which, in turn, supplies power to an electrical resistance heater that is also wound around the cavity walls, (see Fig. 2). The feedback electronics (see Figs. 5 and 6) are designed to maintain a constant temperature difference (approximately $1^{o}C$) between the cavity and the reference cavity. The heat sink, and hence the reference cavity, is temperature controlled to approximately $40^{o}C$. The electrical voltage required to maintain this constant temperature difference is (ideally) proportional to the heat inputs to the cavity. The voltage signal is amplified, converted into digital counts, and transmitted together with housekeeping data, which includes the temperature of the FOV limiter (6) and the base (5) and copper (2) heat sink.

2.3 Conversion Algorithms - Two types of conversion algorithms have been developed from the sensor model. The steady-state linearization (SSL) algorithm, which is of the "gain/offset" form, requires fewer on-line computations; however, it may have larger errors due to the sensor's transient behavior. The modified Kalman Filtering (MKF) algorithm is more accurate under transient conditions, but requires more on-line computations as well as filter design development.

Both algorithms (implicitly or explicitly) account for temperature differences at different nodes, temporal changes in the node temperatures (e.g., dome filter, FOV temperatures), reflection and emission from FOV limiter into the cavity, active cavity heater behavior, electronic feedback control, etc. However, the final accuracy of these algorithms (in comparison to other algorithms) can only be ascertained by testing and simulation under realistic conditions. Thus, ground calibration data must be used for testing and development.

2.4 Measurement Models - Figure 4 presents a functional flow diagram of the sensor, its model and count conversion algorithm, and the error analysis process that is used to

(a) evaluate the sensor model (error e_1),

(b) evaluate the count conversion algorithm (error e_2),

(c) adjust model and algorithm parameters to minimize errors and

(d) establish confidence intervals for the converted data.

This analysis must be performed with sensor characterization and calibration data. Characterization and calibration sources provide a variety of irradiance inputs. At the same time, unfortunately, stray heat inputs leak (radiatively and conductively, directly and indirectly) into the sensors from the sensor/source environment. If a sensor is calibrated in a given environment but is used in a different environement, errors are inevitably introduced unless the effects of the calibration environment are properly accounted for. Thus, it is important to account for these stray heat inputs when calibrating the sensor to empirically update constants for the model and algorithm. Figure 5 shows a block diagram of the procedure and approach that will be used during pre/post calibrations. The nominal values of the model and count conversion parameters have been established in the ground calibration phase. The approach in this phase is to:

(a) determine whether the sensor response has changed,

(b) determine whether the calibration sources have degraded,

(c) update the sensor and source parameters to adequately reflect the new (usually degraded) sensor response,

(d) update the count conversion parameters and

(e) update the confidence intervals on the measurements and count conversion.

Thus, current inflight calibration data is compared to the corresponding previous calibration data to determine if any change in overall response has occurred. If significant differences are found then sensor and source model parameters are varied systematically, and the current data is now compared to simulated data with updated parameters. When updated parameters are obtained error analyses are performed to obtain new confidence intervals, as well as updated count conversion parameters.

Figure 6 shows the functional flow of the measurement process including the sensor/environment interaction, routine data processing and the interaction of flight calibration processing with routine data processing.

3. SIMULATION INPUTS

The following Input Data Table I outlines the constants and parameters which needed To Be Determined (TBD) for the corresponding element numbers and locations for use in the nonscanner sensor model (see sections 5.1 and 5.2).

Input Data Table II further lists the contants and parameters which needed To Be Determined (TBD) for the nonscanner model equations.

INPUT DATA TABLE I

(To Be Determined For The Sensor Simulation)

Constant or Parameter	ELEMENT NUMBER OR LOCATION															
	1_a	1_c	1_e	2_e	3_f	3_d	3_e	4_c	5_b	6_b	7_d	7_t	8_b	8_t	9_a	9_b
ρ_S	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
ρ_L	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
ρ_S^S	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
ρ_L^S	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
ρ_S^d	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
ρ_L^d	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
ϵ_S	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
ϵ_L	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
$\bar{\tau}$															TBD	TBD
τ															TBD	TBD
k	TBD			TBD	TBD			TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
A_k	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
V	TBD			TBD	TBD			TBD	TBD	TBD	TBD		TBD		TBD	
γ	TBD			TBD	TBD			TBD	TBD	TBD	TBD		TBD		TBD	
C	TBD			TBD	TBD			TBD	TBD	TBD	TBD		TBD		TBD	

INPUT DATA TABLE II

L_{k-i} = TBD k = 1, 2, ..., 11 or 12

L_{i-k} = TBD i = 1, 2, ..., 11 or 12

A_{k-i} = TBD k = 1, 2, ..., 11 or 12

h_{k-i} = TBD k = 1, 2, ..., 11 or 12

$\dot{Q}_k$ = TBD k = 1, 2, 3

(dependent on Sensor operation schedule)

$\dot{Q}_k$ = 0 k = 4, 5, 6, 7, 8, 11

F_{j-i} = TBD j & i = 1, 8_b, 8_t, 11_a or 5, 6, 11_b, 12 (with filter dome)

= 1, 8_b, 11_a or 5, 6, 8_t, 11_b, 12 (without filter dome)

$F_{j-i(K-L)}$ = TBD

$E_{FOV(t)}$ = TBD (on account of the variety of radiant sources, the radiant sources must first be defined before determining $E_{FOV(t)}$.)

Housekeeping Data (HKD) & Necessary Information

4. SIMULATION OUTPUTS

After incorporating the constants and parameters from Input Data Tables I and II, the simulation model provided the following outputs. These outputs became inputs for use in further computations.

(a) All parameters defined in Section 5 for use in the Data Validation Algorithm for data products

(b) Noise, bias and time constants and some input variables for use in the Error Analysis problem

(c) Irradiant flux values at FOV of sensor for use in the Inversion Analysis Algorithm.

5. PROCESSING METHOD/ALGORITHM/EQUATIONS:

The equations for the radiative and thermal models of the M/WFOV NS sensors with and without a filter dome are given in Equations 8 and 9 in section 5.2. The coefficients A, D, B_Q, B and b in these equations are computed from Input Data Table I and the variables defined in this section.

Equations 8 and 9 after having defined coefficients A, D, B_Q, B and b, radiometric count readings and HK data, are used in the Count Conversion Algorithms for the analyses of both steady-state and transient responses of the sensors.

A simulation of the sensors will be developed using the parameters defined in this section. This simulation will be used as shown in Figures 5 and 6 during ground and flight calibrations to update model parameters, count conversion parameters, for error analyses and the selection of algorithms.

The following pages show how the coefficients A, D, B_Q, B and b of Equations 8 and 9 are defined.

5.1 NS SENSOR MODEL

The constants, parameters and variables which appear in the following equations are taken from Input Data Table I or defined by the additional equations in Input Data Table II.

The indices of variables are denoted by the node surface identifier shown in the attached figures, e.g., 9a, 3d, etc.

Exchange factors:

$$\varepsilon_{j-i} = F_{j-i} + \left(\prod_{L} \rho_L^s\right) \sum_{K} \rho_K^s \; F_{j-i(K-L)} \tag{1}$$

where i, j = identifiers for each surface

L = 0, 1, 2, ... number of specular image surfaces.

K = 1, 2, 3, ... number of specular real surfaces.

Variable 1:

$$P_{j-i} = (\delta_{ji} - \rho_j^d \, \varepsilon_{j-i})^{-1} \tag{2}$$

where i, j = identifiers for each surface

Variable 2:

$$H_{kji} = \sum_{j} \varepsilon_{k-j} \, P_{j-i} \tag{3}$$

where k, j, i = identifiers for each surface

Variable 3 & 4:

With filter dome:

$$\bar{G} = \left[1 - \bar{\tau}_9^2 \; H_{9_a j 9_a} \; H_{9_b m 9_b}\right]^{-1} \tag{4}$$

where $j = 1, 8_b, 8_t, 9_a$

$m = 5, 6, 9_b, 10$

Without filter dome:

$$G = \left[1 - \tau_9^2 \; H_{9_a j 9_a} \; H_{9_b m 9_b}\right]^{-1} \tag{5}$$

where $j = 1, 8_b, 9_a$

$m = 5, 6, 8_t, 9_b, 10$

Variable 5:

$$M_k = (V\gamma C)_k \tag{6}$$

where k = node number

Variable 6:

$$R_{ki} = \frac{L_{k-i}}{k_k \; A_{k-1}} + \frac{1}{h_{k-i} \; A_{k-i}} + \frac{L_{i-k}}{k_i \; A_{k-i}} \tag{7}$$

where k, i = node number

Variable 7:

$$A_{11} = (-\frac{1}{R_{12}} - K_1 K_2 K_3)/M_1$$

$$A_{12} = \frac{1}{R_{12}M_1}, \qquad A_{13} = K_1K_2K_3, \qquad A_{1\ 10} = K_3$$

all other 1st row elements in the A matrix are zero (see Eq. 8).

$$A_{21} = \frac{1}{R_{21}M_2}$$

$$A_{22} = -\left(\frac{1}{R_{21}} + \frac{1}{R_{24}} + \frac{1}{R_{23}} + \frac{1}{R_{27}}\right) * \left(\frac{1}{M_2}\right)$$

$$A_{23} = \frac{1}{R_{23}M_2}$$

$$A_{24} = \frac{1}{R_{24}M_2}, \qquad A_{27} = \frac{1}{R_{27}M_2}$$

all other 2nd row A matrix elements are zero.

$$A_{32} = \frac{1}{R_{32}M_3}, \qquad A_{33} = -\frac{1}{R_{32}M_3}$$

all other 3rd row A matrix elements are zero.

$$A_{42} = \frac{1}{R_{42}M_4}, \qquad A_{44} = -\left(\frac{1}{R_{42}} + \frac{1}{R_{45}} + \frac{1}{R_{48}}\right) * \left(\frac{1}{M_4}\right)$$

$$A_{45} = \frac{1}{R_{45}M_4}, \qquad A_{48} = \frac{1}{R_{48}M_4}$$

all other 4th row A matrix elements are zero.

$$A_{54} = \frac{1}{R_{54}M_5}, \qquad A_{55} = -\left(\frac{1}{R_{54}} + \frac{1}{R_{56}} + \frac{1}{R_{58}} + \frac{1}{R_{511}\left(\frac{1}{R_{57}} + \frac{1}{R_{5\ 9}}\right)}\right) * \left(\frac{1}{M_5}\right)$$

$$A_{57} = \frac{1}{R_{57}\ M_5}$$

$A_{56} = \frac{1}{R_{56}M_5}$, $A_{58} = \frac{1}{R_{58}M_5}$, $A_{59} = \frac{1}{R_{59}M_5}$, $A_{511} = \frac{1}{R_{511}M_5}$ (with filter dome

all other 5th row A matrix elements are zero.

$A_{65} = \frac{1}{R_{65}M_6}$, $A_{66} = -\frac{1}{R_{65}M_6}$

all other 6th row A matrix elements are zero.

$A_{72} = \frac{1}{R_{72}M_7}$, $A_{77} = \left(-\frac{1}{R_{72}M_7} - \frac{1}{R_{75}M_7}\right)$, $A_{75} = \frac{1}{R_{75}M_7}$

all other 7th row A matrix elements are zero.

$A_{84} = \frac{1}{R_{84}M_8}$, $A_{85} = \frac{1}{R_{85}M_8}$

$A_{88} = -\left(\frac{1}{R_{84}} + \frac{1}{R_{85}} + \frac{1}{R_{89}}\right) * \left(\frac{1}{M_8}\right)$ (with filter dome)

or $= -\left(\frac{1}{R_{84}} + \frac{1}{R_{85}}\right) * \left(\frac{1}{M_8}\right)$ (without filter dome)

$A_{8\,11} = \frac{1}{R_{118}M_8}$ (with filter dome)

all other 8th row A matrix elements are zero.

For a sensor with filter dome <u>only</u>:

$A_{811} = \frac{1}{R_{95}M_{11}}$

$A_{118} = \frac{1}{R_{118}M_8}$

$A_{11\,11} = \left(-\frac{1}{R_{115}} + \frac{1}{R_{118}}\right) * \left(\frac{1}{M_{11}}\right)$

all other 9th row A matrix elements are zero.

Considering the box beam as an additional node designeated "node 9",

$$A_{95} = \frac{1}{R_{105}M_{10}} \quad , \qquad A_{99} = -\left(\frac{1}{R_{95}M_9}\right)$$

$$A_{10\,1} = -\frac{K_1}{M_{10}} , \qquad A_{10\,3} = \frac{K_1}{M_{10}} \quad \text{where } M_{10} = 1$$

all other 10th row elements are zero.

Variable 8:

The subscripts S and L denote the shortwave and longwave properties of surfaces in the enclosure, respectively. That is, the radiative properties in the bracket with subscript S are defined by shortwave characteristics of a surface. These properties are taken from Input Data Table I.

To avoid the repetition of writing, we write as the following example: In the following equations, ε must be read as ϵ, $\varepsilon \rightarrow \epsilon$

EXAMPLE:

$$\left[A_{1_e}(1-\rho_{1_e})\varepsilon_{3_e}H_{1_e j 3_e}\right]_{S,L} = \left(A_{1_e}(1-\rho_{1_e})\varepsilon_{3_e}H_{1_e j 3_e}\right)_S + \left(A_{1_e}(1-\rho_{1_e})\varepsilon_{3_e}H_{1_e j 3_e}\right)_L$$

$$D_{11} = \left(\frac{\sigma}{M_1}\right)\Big(A_{1_c}\varepsilon_{1_c}\{(1-\rho_{1_c})H_{1_c j 1_c}-1\} + A_{1_e}\varepsilon_{1_e}\{(1-\rho_{1_e})H_{1_e j 1_e}-1\}$$

$$+ A_{1_a}(1-\rho_1)\varepsilon_1\{H_{1j1}-1 + \bar{\tau}_9^2\, \bar{G}\, H_{11_b m 11_b}H_{11_a j 1}H_{1j11_a}\} \Big)_{S,L}$$

$$D_{12} = \left(\frac{\sigma}{M_1}\right)\left(A_{1_c}(1-\rho_{1_c})\varepsilon_2 H_{1_c j 2} + A_{1_e}(1-\rho_{1_e})\varepsilon_2 H_{1_e j 2}\right)_{S,L}$$

$$D_{13} = \left(\frac{\sigma}{M_1}\right)\left(A_{1_e}(1-\rho_{1_e})\varepsilon_{3_e} H_{1_e j 3_e}\right)_{S,L}$$

$$D_{14} = \left(\frac{\sigma}{M_1}\right)\left(A_{1_c}(1-\rho_{1_c})\varepsilon_4 H_{1_c j 4}\right)_{S,L}$$

$$D_{15} = \left(\frac{\sigma}{M_1}\right)\left(A_{1_a}(1-\rho_1)\varepsilon_5 \bar{\tau}_{11} \bar{G}\, H_{1_b m 5} H_{1 j 11_a}\right)_{S,L}$$

$$D_{16} = \left(\frac{\sigma}{M_1}\right)\left(A_{1_a}(1-\rho_1)\varepsilon_6 \bar{\tau}_{11} \bar{G}\, H_{1_b m 6} H_{1 j 11_a}\right)_{S,L}$$

$$D_{17} = 0$$

$$D_{18} = \left(\frac{\sigma}{M_1}\right)\left(A_{1_a}(1-\rho_1)\{\varepsilon_{8_b} H_{1 j 8_b} + \varepsilon_{8_t} H_{1 j 8_t} + \bar{\tau}_{11}^{2} \bar{G} H_{1 j 11_a} H_{11_b m 1_b} (\varepsilon_{8_b} H_{11_a j 8_b} + \varepsilon_{8_t} H_{11_a j 8_t})\}\right)_{S,L}$$

$$D_{111} = \left(\frac{\sigma}{M_1}\right)\left(A_{1_a}(1-\rho_1)\{\varepsilon_{11_a} H_{1 j 11_a} + \bar{\tau}_{11} \bar{G} H_{1 j 11_a} H_{11_b m 11_b} (\varepsilon_{11_b} + \bar{\tau}_{11} \varepsilon_{11a} H_{11_a j 11_a})\}\right)_{S,L}$$

$$D_{1\,10} = 0 = D_{1\,11} = D_{1\,9}$$

$$D_{21} = \left(\frac{\sigma}{M_2}\right)\left(A_{2_e}(1-\rho_2)\ \varepsilon_{1_e}\ H_{2 j 1_e}\right)_{S,L}$$

$$D_{22} = \left(\frac{\sigma}{M_2}\right)\left(A_{2_e}\varepsilon_2\{(1-\rho_2)\ H_{2j2} - 1\}\right)_{S,L}$$

$$D_{23} = \left(\frac{\sigma}{M_2}\right)\left(A_{2_e}(1-\rho_2)\ \varepsilon_{3_e}\ H_{2j3_e}\right)_{S,L}$$

$$D_{24} = D_{25} = D_{26} = D_{27} = D_{28} = D_{29} = D_{2\ 10} = 0 = D_{2\ 11}$$

$$D_{31} = \left(\frac{\sigma}{M_3}\right)\left(A_{3_e}(1-\rho_{3_e})\ \varepsilon_{1_e}\ H_{3_ej1_e}\right)_{S,L}$$

$$D_{32} = \left(\frac{\sigma}{M_3}\right)\left(A_{3_e}(1-\rho_{3_e})\ \varepsilon_2\ H_{3_ej2} + A_{3_d}(1-\rho_{3_d})\ \varepsilon_2\ H_{3_dj2}\right)_{S,L}$$

$$D_{33} = \left(\frac{\sigma}{M_3}\right)\Big(A_{3_e}\varepsilon_{3_e}\{(1-\rho_{3_e})H_{3_ej3_e}-1\} + A_{3_d}\varepsilon_{3_d}\{(1-\rho_{3_d})H_{3_dj3_d}-1\}$$

$$+ A_{3_f}\varepsilon_3\{(1-\rho_3)H_{3j3}-1\}\Big)_{S,L}$$

$$D_{34} = D_{35} = D_{36} = 0$$

$$D_{37} = \left(\frac{\sigma}{M_3}\right)\left(A_{3_d}(1-\rho_{3_d})\ \varepsilon_7 H_{3_dj7} + A_{3_f}(1-\rho_3)\ \varepsilon_7 H_{3j7}\right)_{S,L}$$

$$D_{38} = D_{39} = D_{3\ 10} = 0 = D_{3\ 11}$$

$$D_{41} = \left(\frac{\sigma}{M_4}\right)\left(A_{4_c}(1-\rho_4)\ \varepsilon_{1_c}\ H_{4j1_c}\right)_{S,L}$$

$$D_{42} = \left(\frac{\sigma}{M_4}\right)\left(A_{4_c}(1-\rho_4)\ \varepsilon_2\ H_{4j2}\right)_{S,L}$$

$$D_{43} = 0$$

$$D_{44} = \left(\frac{\sigma}{M_4}\right) \left(A_{4_c}\, \varepsilon_4 \{(1-\rho_4)\, H_{4j4} - 1\} + \bar{A}_4 \bar{\varepsilon}_4 \{(1-\bar{\rho}_4)\bar{H}_{4j4} - 1\}\right)_{S,L}$$

$$D_{46} = D_{47} = D_{48} = D_{49} = D_{410} = D_{4\ 11} = 0\ , \quad D_{45} = \left(\frac{\sigma}{M_4}\right)\left(\bar{A}_4 (1-\bar{\rho}_4)\bar{\varepsilon}_5 \bar{H}_{4j5}\right)_{S,L}$$

$$D_{51} = \left(\frac{\sigma}{M_5}\right) \left(A_5\ \varepsilon_1 (1-\rho_5)\ \bar{\tau}_{11} \bar{G}\ H_{11_a j1}\ H_{5m11_b}\right)_{S,L}$$

$$D_{52} = D_{53} = 0\ , \quad D_{54} = \left(\frac{\sigma}{M_5}\right)\left(\bar{A}_{54} (1-\bar{\rho}_5)\bar{\varepsilon}_4 \bar{H}_{5j4}\right)_{S,L}$$

$$D_{55} = \left(\frac{\sigma}{M_5}\right) \left(A_5 \varepsilon_5 \{(1-\rho_5)\ H_{5m5} - 1 + \bar{\tau}_{11}^2 (1-\rho_5)\bar{G}\ H_{11_a j11_a}\ H_{11_b m5}\ H_{5m11_b}\} + \bar{A}_5 \bar{\varepsilon}_5 \{(1-\bar{\rho}_5)\bar{H}_{5j5} - 1\}\right)_{S,L}$$

$$D_{56} = \left(\frac{\sigma}{M_5}\right) \left(A_5 \varepsilon_6 \{(1-\rho_5)\ H_{5m6} + \bar{\tau}_{11}^2 (1-\rho_5)\bar{G}\ H_{11_a j11_a}\ H_{11_b m6}\ H_{5m11_b}\}\right)_{S,L}$$

$$D_{57} = 0$$

$$D_{58} = \left(\frac{\sigma}{M_5}\right) \left(A_5 \bar{\tau}_{11} (1-\rho_5)\bar{G}\ H_{5m11_b}\ (\varepsilon_{8_b} H_{11_a j8_b} + \varepsilon_{8_t} H_{11_a j8_t})\right)_{S,L}$$

$$D_{511} = \left(\frac{\sigma}{M_5}\right) \left(A_5 (1-\rho_5)\{\varepsilon_{11_b} H_{5m11_b} + \bar{\tau}_{11}\bar{G}\ H_{5m11_b}\ H_{11_a j11_a} (\varepsilon_{11_a} + \bar{\tau}_{11} \varepsilon_{11_b} H_{11_b m11_b})\}\right)_{S,L}$$

$$D_{5\,10} = 0 = D_{5\,11} = D_{5\,9}$$

$$D_{61} = \left(\frac{\sigma}{M_6}\right)\left(A_6 \varepsilon_1 \bar{\tau}_{11}(1-\rho_6)\bar{G}\; H_{11_a j1}\; H_{6m11_b}\right)_{S,L}$$

$$D_{62} = D_{63} = D_{64} = 0$$

$$D_{65} = \left(\frac{\sigma}{M_6}\right)\left(A_6 \varepsilon_5 (1-\rho_6)\{H_{6m5} + \bar{\tau}_{11}^2\, \bar{G}\; H_{6m11_a}\; H_{9_a j 11_a}\; H_{11_b m5}\}\right)_{S,L}$$

$$D_{66} = \left(\frac{\sigma}{M_6}\right)\left(A_6 \varepsilon_6 \{(1-\rho_6)\; H_{6m6} + \bar{\tau}_{11}^2 (1-\rho_6)\bar{G}\; H_{6m11_a}\; H_{11_a j 11_a}\; H_{11_b m5} - 1\}\right)_{S,L}$$

$$D_{67} = 0$$

$$D_{68} = \left(\frac{\sigma}{M_6}\right)\left(A_6 \bar{\tau}_{11}(1-\rho_6)\bar{G}\; H_{6m11_b}(\varepsilon_{8_b}\; H_{11_a j 8_b} + \varepsilon_{8_t}\; H_{11_a j 8_t})\right)_{S,L}$$

$$D_{611} = \left(\frac{\sigma}{M_6}\right)\left(A_6 (1-\rho_6) H_{6m11_a}\{\varepsilon_{11_b} + \bar{\tau}_{11}\bar{G}\; H_{11_a j 11_a}(\varepsilon_{11_a} + \bar{\tau}_{11}\varepsilon_{11_b}\; H_{11_b m 11_b})\}\right)_{S,L}$$

$$D_{6\,10} = 0 = D_{6\,11} = D_{6\,9}$$

$$D_{71} = 0$$

$$D_{72} = \left(\frac{\sigma}{M_7}\right)\left(A_{7_d}(1-\rho_7)\; \varepsilon_2\; H_{7j2}\right)_{S,L}$$

$$D_{73} = \left(\frac{\sigma}{M_7}\right)\left(A_{7_d}(1-\rho_7)\,\varepsilon_{3_d}\,H_{7j3_d} + A_{7_f}(1-\rho_7)\,\varepsilon_3\,H_{7j3}\right)_{S,L}$$

$$D_{74} = D_{75} = D_{76} = 0$$

$$D_{77} = \left(\frac{\sigma}{M_7}\right)\left(A_{7_d}\,\varepsilon_{7_d}\{(1-\rho_7)\,H_{7_dj7_d}-1\} + A_{7_f}\,\varepsilon_7\{(1-\rho_7)\,H_{7j7}-1\}\right)_{S,L}$$

$$D_{78} = D_{79} = D_{7\ 10} = 0 = D_{7\ 11} = D_{7\ 12}$$

$$D_{81} = \left(\frac{\sigma}{M_8}\right)\Big(A_8\,\varepsilon_1\{(1-\rho_{8_b})H_{8_bj1} + (1-\rho_{8_t})H_{8_tj1}$$

$$+ \bar{\tau}_{11}^2\bar{G}\,H_{11_bm11_b}\,H_{11_aj1}\left((1-\rho_{8_b})H_{8_bj11_a} + (1-\rho_{8_t})H_{8_tj11_a}\right)\}\Big)_{S,L}$$

$$D_{82} = D_{83} = D_{84} = 0$$

$$D_{85} = \left(\frac{\sigma}{M_8}\right)\left(A_8\,\varepsilon_5\,\bar{\tau}_{11}\bar{G}\,H_{11_bm5}\{(1-\rho_{8_b})H_{8_bj11_a} + (1-\rho_{8_t})H_{8_tj11_a}\}\right)_{S,L}$$

$$D_{86} = \left(\frac{\sigma}{M_8}\right)\left(A_8\,\varepsilon_6\,\bar{\tau}_{11}\,\bar{G}\,H_{11_bm6}\{(1-\rho_{8_b})H_{8_bj11_a} + (1-\rho_{8_t})H_{8_tj11_a}\}\right)_{S,L}$$

$$D_{87} = 0$$

$$D_{88} = \left(\frac{\sigma}{M_8}\right)\left(A_8\{(1-\rho_{8_b})(\varepsilon_{8_b}H_{8_bj8_a} + \varepsilon_{8_t}H_{8_bj8_t}) + (1-\rho_{8_t})(\varepsilon_{8_b}H_{8_tj8_b} + \varepsilon_{8_t}H_{8_tj8_t})\right.$$

$$- \varepsilon_{8_b} - \varepsilon_{8_t} + \bar{\tau}_{11}^{2}\bar{G}\, H_{11_bj11_b}(\varepsilon_{8_b}H_{11_aj8_b} + \varepsilon_{8_t}H_{11_aj8_t})\{(1-\rho_{8_b})H_{8_bj11a}$$

$$\left. + (1-\rho_{8_t})H_{8_tj11_a}\}\}\right)_{S,L}$$

$$D_{811} = \left(\frac{\sigma}{M_8}\right)\left(A_8\varepsilon_{11_a}\{(1-\rho_{8_b})H_{8_bj11_a} + (1-\rho_{8_t})H_{8_tj11_a}\}\right.$$

$$\left.\{1 + \bar{\tau}_{11}\bar{G}(H_{11_bm11_b} + \bar{\tau}_{11}\, H_{11_aj11a}\, H_{11_bm11_b})\}\right)_{S,L}$$

$$D_{8\,10} = 0 = D_{8\,11} = D_{8\,9}$$

$$D_{111} = \left(\frac{\sigma}{M_{11}}\right)\left(A_{11}\varepsilon_1\, H_{11aj1}\{1-\rho_{11_a} + \bar{\tau}_{11}\bar{G}\left((1-\rho_{11_b})H_{11_bm11_b} - 1\right)\right.$$

$$\left. + \bar{\tau}_{11}^{2}\bar{G}\, H_{11_bm11_b}\left((1-\rho_{11_a})H_{11_aj11_a} - 1\right)\}\right)_{S,L}$$

$$D_{112} = D_{113} = D_{114} = 0$$

$$D_{11\,5} = \left(\frac{\sigma}{M_{11}}\right)\left(A_{11}\,\varepsilon_5 H_{11_b m5}\{ 1-\rho_{11_b} + \bar{\tau}_{11}\bar{G}\left((1-\rho_{11_a})H_{11_a j 11_a} - 1\right)\right.$$

$$\left. + \bar{\tau}^2_{11}\bar{G}\, H_{11_a j 11_a}\left((1-\rho_{11_b})H_{11_b m 11_b} - 1\right)\}\right)_{S,L}$$

$$D_{11\,6} = \left(\frac{\sigma}{M_{11}}\right)\left(A_{11}\,\varepsilon_5 H_{11_b m6}\{ 1-\rho_{11_b} + \bar{\tau}_{11}\bar{G}\left((1-\rho_{11_a})H_{11_a j 11_a} - 1\right)\right.$$

$$\left. + \bar{\tau}^2_{11}\bar{G}\, H_{11_a j 11_a}\left((1-\rho_{11_b})H_{11_b n 11_b} - 1\right)\}\right)_{S,L}$$

$$D_{11\,7} = 0$$

$$D_{11\,8} = \left(\frac{\sigma}{M_{11}}\right)\left(A_{11}(\varepsilon_{8_b} H_{11_a j 8_b} + \varepsilon_{8_t} H_{11_a j 8_t})\{ 1-\rho_{11_a} + \bar{\tau}_{11}\bar{G}\left((1-\rho_{11_b})H_{11_b m 11_b} - 1\right)\right.$$

$$\left. + \bar{\tau}^2_{11}\bar{G}\, H_{11_b m 11_b}\left((1-\rho_{11_a})H_{11_a j 11_a} - 1\right)\}\right)_{S,L}$$

$$D_{11\,11} = \left(\frac{\sigma}{M_{11}}\right)\left(A_{11}\{ (1-\rho_{11_a})H_{11_a j 11_a} - 1\}\{\varepsilon_{11_a} + \bar{\tau}_{11}\bar{G}\, H_{11_b m 11_b}(\varepsilon_{9_b} + \bar{\tau}_9\, {}_{9_a}H_{9_a j 9_a})\}\right.$$

$$\left. + \{ (1-\rho_{11_b})H_{11_b m 11_b} - 1\}\{\varepsilon_{11_b} + \bar{\tau}_{11}\bar{G}\, H_{11_a j 11_a}(\varepsilon_{11_a} + \bar{\tau}_{11}\varepsilon_{11_b} H_{11_b m 11_b}\}\right)_{S,L}$$

$$D_{11\,10} = 0 = D_{11\,11}$$

$$D_{10\,1} = D_{10\,2} = D_{10\,3} = D_{10\,4} = D_{10\,5} = D_{10\,6} = D_{10\,7} = D_{10\,8} =$$

$$D_{10\,9} = D_{10\,10} = 0 = D_{10\,11} = D_{10\,12}$$

$$D_{11\,1} = D_{11\,2} = D_{11\,3} = D_{11\,4} = D_{11\,5} = D_{11\,6} = D_{11\,7} = D_{11\,8} =$$

$$D_{11\,9} = D_{11\,10} = D_{11\,11} = 0 = D_{11\,12}$$

<u>Variable 9:</u>

$$B_Q = \begin{bmatrix} 0 \\ \frac{A_{q2}}{M_2} \\ 0 \\ \frac{A_{q4}}{M_4} \\ 0 \\ 0 \\ \frac{A_{q7}}{M_7} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

†† q2, q4, and q7 are subscripts.

<u>Variable 10:</u>

$$BE = B_S E_S + B_L B_L$$

$$(B_1)_{S,L} = \left(\frac{1}{M_1}\right)\left(A_{1a}(1-\rho_1)\bar{\tau}\ \tau_{10}\bar{G}\ H_{1j\ a}\ H_{\ bm10}\right)_{S,L}$$

$$(B_5)_{S,L} = \left(\frac{1}{M_5}\right)\left(A_5\tau_{10}(1-\rho_5)\{H_{5m10} + \bar{\tau}_9^2\bar{G}\ H_{9_aj9_a}\ H_{9_bm10}\ H_{5m9_b}\}\right)_{S,L}$$

$$(B_6)_{S,L} = \left(\frac{1}{M_6}\right)\left(A_6(1-\rho_6)\tau_{10}\{H_{6m10} + \bar{\tau}_9^2\bar{G}\ H_{9_aj9_a}\ H_{9_bm10}\ H_{6m9_b}\}\right)_{S,L}$$

$$(B_8)_{S,L} = \left(\frac{1}{M_8}\right)\left(A_8\bar{\tau}_9\tau_{10}\bar{G}\ H_{9_bm10}\{(1-\rho_{8_b})H_{8_bj9_a} + (1-\rho_{8_t})H_{8_tj9_a}\}\right)_{S,L}$$

$$(B_9)_{S,L} = \left(\frac{1}{M_9}\right)\Big(A_9\tau_{10}H_{9_bm10}\{1-\rho_{8_b} + \bar{\tau}_9\bar{G}\left((1-\rho_{9_a})H_{9_aj9_a} - 1\right)$$

$$+ \bar{\tau}_9^2\bar{G}\ H_{9_aj9_a}\left((1-\rho_{9_b})H_{9_bm9_b} - 1\right)\}\Big)_{S,L}$$

All other elements are zero.

<u>Variable 11</u>:

$$b_1 = K_1K_2K_3b_{10}/M_1$$

$$b_{10} = (K_1b_{10} + n_{10})/M_{10} \rightarrow b_{10} = \frac{n_{10}}{(1-K_1)}\ ,\quad M_{10} = 1.$$

All other bs are zero.

<u>Without Filter Dome</u> (total channel)

Variable 12

$$D_{11} = \left(\frac{\sigma}{M_1}\right)\left(A_{1_c}\varepsilon_{1_c}\{(1-\rho_{1_c})H_{1_cj1_c} - 1\} + A_{1_e}\varepsilon_{1_e}\{(1-\rho_{1_e})H_{1_ej1_e} - 1\}\right.$$

$$\left. + A_{1_a}\varepsilon_1\{(1-\rho_1)H_{1j1} - 1 + \tau_9^2(1-\rho_1)G\ H_{1j9_a}\ H_{9_bm9_b}\ H_{9_aj1}\}\right)$$

$$D_{12} = \left(\frac{\sigma}{M_1}\right)\left(A_{1_c}(1-\rho_{1_c})\varepsilon_2 H_{1_cj2} + A_{1_e}(1-\rho_{1_e})\varepsilon_2 H_{1_ej2}\right)$$

$$D_{13} = \left(\frac{\sigma}{M_1}\right)\left(A_{1_e}(1-\rho_{1_c})\varepsilon_{3_e} H_{1_ej3e}\right)$$

$$D_{14} = \left(\frac{\sigma}{M_1}\right)\left(A_{1_c}(1-\rho_{1_c})\varepsilon_4 H_{1_cj4}\right)$$

$$D_{15} = \left(\frac{\sigma}{M_1}\right)\left(A_{1_a}\varepsilon_5\tau_9(1-\rho_1)G\ H_{1j9_a}\ H_{9_bm5}\right)$$

$$D_{16} = \left(\frac{\sigma}{M_1}\right)\left(A_{1_a}\varepsilon_6\tau_9(1-\rho_1)G\ H_{1j9_a}\ H_{9_bm6}\right)$$

$$D_{17} = 0$$

$$D_{18} = \left(\frac{\sigma}{M_1}\right) \left((1-\rho_1)A_{1_a}\{\varepsilon_{8_b}H_{1j8_b} + \tau_{11}G\ H_{1j11a}(\varepsilon_{8t}H_{11bm8t}\right.$$

$$\left. + \tau_{11}\varepsilon_{8_b}H_{11_bm11_b}\ H_{11_aj8_b})\}\right)$$

$$D_{19} = D_{1\ 10} = 0 = D_{1\ 11} = D_{1\ 12}$$

$$D_{21} = \left(\frac{\sigma}{M_2}\right)\left(A_{2_e}(1-\rho_2)\varepsilon_{1_e}\ H_{2j1_e}\right)$$

$$D_{22} = \left(\frac{\sigma}{M_2}\right)\left(A_{2_e}\{(1-\rho_2)\varepsilon_2\ H_{2j2} - \varepsilon_2\}\right)$$

$$D_{23} = \left(\frac{\sigma}{M_2}\right)\left(A_{2_e}(1-\rho_2)\varepsilon_{3_e}\ H_{2j3_e}\right)$$

$$D_{24} = D_{25} = D_{26} = D_{27} = D_{28} = D_{2\ 10} = 0 = D_{2\ 11} = D_{29} = D_{2\ 12}$$

$$D_{31} = \left(\frac{\sigma}{M_3}\right)\left(A_{3_e}(1-\rho_{3_e})\varepsilon_{1_e}\ H_{3_ej1_e}\right)$$

$$D_{32} = \left(\frac{\sigma}{M_3}\right)\left(A_{3_e}(1-\rho_{3_e})\varepsilon_2\ H_{3_ej2} + A_{3_d}(1-\rho_{3_d})\varepsilon_2\ H_{3_dj2}\right)$$

$$D_{33} = \left(\frac{\sigma}{M_3}\right)\left(A_{3_e}\{(\varepsilon_{3_e}(1-\rho_{3_e})H_{3_ej3_e} - \varepsilon_{3_e}\} + A_{3_d}\varepsilon_{3_d}\{(1-\rho_{3_d})H_{3_dj3_d} - 1\}\right.$$

$$\left. + A_{3_f}\varepsilon_3\{(1-\rho_3)H_{3j3} - 1\}\right)$$

$$D_{34} = D_{35} = D_{36} = 0$$

$$D_{37} = \left(\frac{\sigma}{M_3}\right)\left(A_{3_d}(1-\rho_{3_d})\varepsilon_7 H_{3_d j7} + A_{3_f}(1-\rho_3)\varepsilon_7 H_{3j7}\right)$$

$$D_{38} = D_{3\ 10} = 0 = D_{39} = D_{3\ 11} = D_{3\ 12}$$

$$D_{41} = \left(\frac{\sigma}{M_4}\right)\left(A_{4_c}(1-\rho_4)\varepsilon_{1_c} H_{4j1_c}\right)$$

$$D_{42} = \left(\frac{\sigma}{M_4}\right)\left(A_{4_c}(1-\rho_4)\varepsilon_2 H_{4j2}\right)$$

$$D_{43} = 0$$

$$D_{44} = \left(\frac{\sigma}{M_4}\right)\left(A_{4_c}\varepsilon_4\{(1-\rho_4)H_{4j4} - 1\} + \bar{A}_4\bar{\varepsilon}_4\{(1-\bar{\rho}_4)\bar{H}_{4j4} - 1\}\right)$$

$$D_{45} = \left(\frac{\sigma}{M_4}\right)\left(\bar{A}_4(1-\bar{\rho}_4)\bar{\varepsilon}_5\bar{H}_{4j5}\right)$$

$$D_{46} = D_{47} = D_{48} = D_{49} = D_{4\ 10} = 0 = D_{11\ 11}$$

$$D_{51} = \left(\frac{\sigma}{M_5}\right)\left(A_5\varepsilon_1\tau_{11}(1-\rho_5)G\ H_{5m11a}\ H_{11aj1}\right)$$

$$D_{52} = D_{53} = 0\ , \qquad D_{54} = \left(\frac{\sigma}{M_5}\right)\left(\bar{A}_5(1-\bar{\rho}_5)\bar{\varepsilon}_5\bar{H}_{5j4}\right)$$

$$D_{55} = \left(\frac{\sigma}{M_5}\right)\left(A_5\varepsilon_5\ \{(1-\ _5)H_{5m5} - 1 + \tau_{11}^2(1-\rho_5)G\ H_{5m_{11b}}\ H_{11_a j 11_a}\ H_{11_b m5}\}\right.$$
$$\left. + \bar{A}_5\bar{\varepsilon}_5\{(1-\bar{\rho}_5)\bar{H}_{5j5} - 1\}\right)$$

$$D_{56} = \left(\frac{\sigma}{M_5}\right)\left(A_5\varepsilon_6(1-\rho_5)H_{5m6} + \tau_{11}^2 G\ H_{5m1_b}\ H_{1_a j 1_a}\ H_{1_b m6}\right)$$

$$D_{57} = 0$$

$$D_{58} = \left(\frac{\sigma}{M_5}\right)\left(A_5(1-\rho_5)\{\varepsilon_{8_t} H_{5m8_t} + \tau_{11} G\ H_{5m1_b}(\varepsilon_{8_b} H_{1_a j 8_b} + \tau_{11}\varepsilon_{8_t} H_{1_a j 1_a}\ H_{1_b m8_t})\}\right)$$

$$D_{5\ 10} = 0 = D_{59} = D_{5\ 11} = D_{5\ 12}$$

$$D_{61} = \left(\frac{\sigma}{M_6}\right)\left(A_6\varepsilon_1\tau_{11}(1-\rho_6)G\ H_{6m1_b}\ H_{1_a j 1}\right)$$

$$D_{62} = D_{63} = D_{64} = 0$$

$$D_{65} = \left(\frac{\sigma}{M_6}\right)\left(A_6\varepsilon_5(1-\rho_6)\{H_{6m5} + \tau_{11}^2 G\ H_{6m1_b}\ H_{1_a j 1_a}\ H_{1_b m5}\}\right)$$

$$D_{67} = 0$$

$$D_{68} = \left(\frac{\sigma}{M_6}\right)\left(A_6(1-\rho_6)\{\varepsilon_{8_t} H_{6m8_t} + \tau_{11} G\ H_{6m1_b}(\varepsilon_{8_b} H_{1_a j 8_b} + \tau_{11}\varepsilon_{8_t} H_{1_a j 1_a}\ H_{1_b m8_t})\}\right)$$

$$D_{6\ 10} = 0 = D_{69} = D_{6\ 11} = D_{6\ 12}$$

$$D_{71} = 0$$

$$D_{72} = \left(\frac{\sigma}{M_7}\right) \left(A_{7_d}(1-\rho_7)\varepsilon_2 H_{7j2}\right)$$

$$D_{73} = \left(\frac{\sigma}{M_7}\right) \left(A_{7_d}(1-\rho_7)\varepsilon_{3_d} H_{7j3_d} + A_{7_f}(1-\rho_7)\varepsilon_3 H_{7j3}\right)$$

$$D_{74} = D_{75} = D_{76} = 0$$

$$D_{77} = \left(\frac{\sigma}{M_7}\right)\left(A_{7_d}\varepsilon_{7_d}\{ (1-\rho_7)H_{7_dj7_d} - 1\} + A_{7_f}\varepsilon_7\{ (1-\rho_7)H_{7j7} - 1\}\right)$$

$$D_{78} = 0 = D_{7\ 10} = D_{79} = D_{7\ 11} = D_{7\ 12}$$

$$D_{81} = \left(\frac{\sigma}{M_8}\right) \left(A_{8_b}\varepsilon_1(1-\rho_{8_b})\{H_{8_bj1} + \tau_{11}^2 G\ H_{8_bj11_a}\ H_{11_bm11_b}\ H_{11_aj1}\}\right.$$

$$\left. + \ A_{8_t}\varepsilon_1\tau_{11}(1-\rho_{8_t})G\ H_{8_tm11_b}\ H_{11_aj1}\right)$$

$$D_{82} = D_{83} = D_{84} = 0$$

$$D_{85} = \left(\frac{\sigma}{M_8}\right)\left(A_{8_b}\varepsilon_5\tau_{11}(1-\rho_{8_b})G\ H_{8_bj11_a}\ H_{11_bm5} + A_{8_t}\varepsilon_5(1-\rho_{8_t})\right.$$

$$\left.\{H_{8_tm5} + \tau_{11}^2 G\ H_{8_tm11_b}\ H_{11_aj11_a}\ H_{11_bm5}\}\right)$$

$$D_{86} = \left(\frac{\sigma}{M_8}\right)\Big(A_{8_b}\varepsilon_6\tau_{11}(1-\rho_{8_b})G\ H_{8_bj11_a}\ H_{11_bm6} + A_{8_t}\varepsilon_6(1-\rho_{8_t})$$

$$\{H_{8_tm6} + \tau_{11}^2 G\ H_{8_tm11_b}\ H_{11_aj11_a}\ H_{11_bm6}\}\Big)$$

$$D_{87} = 0$$

$$D_{88} = \left(\frac{\sigma}{M_8}\right)\Big(A_{8_b}\{\varepsilon_{8_b}\big((1-\rho_{8_b})H_{8_bj8_b}-1\big)+\tau_{11}(1-\rho_{8_b})G\ H_{8_bj11_a}(\varepsilon_{8_t}H_{11_bm8_t}$$

$$+\tau_{11}\varepsilon_{8_b}H_{11_bm11_b}\ H_{11_aj8_b})\}+A_{8_t}\{\varepsilon_{8_t}\big((1-\rho_{8_t})H_{8_tm8_t}-1\big)$$

$$+\tau_{11}(1-\rho_{8_t})G\ H_{8_tm11_b}(\varepsilon_{8_b}H_{11_aj8_b}+\tau_{11}\varepsilon_{8_t}H_{11_aj11_a}\ H_{11_bm8_t})\}\Big)$$

$$D_{8\ 10} = 0 = D_{89} = D_{8\ 11} = D_{8\ 12}$$

$$D_{10\ 1} = D_{10\ 2} = D_{10\ 3} = D_{10\ 4} = D_{10\ 5} = D_{10\ 6} = D_{10\ 7} = D_{10\ 8} =$$

$$D_{10\ 10} = 0 = D_{10\ 9} = D_{10\ 11} = D_{10\ 12}$$

$$D_{11\ 1} = D_{11\ 2} = D_{11\ 3} = D_{11\ 4} = D_{11\ 5} = D_{11\ 6} = D_{11\ 7} = D_{11\ 8} = D_{11\ 9}$$

$$D_{11\ 10} = D_{11\ 11} = 0 = D_{11\ 12} = 0$$

B_Q = same as Variable 9

Variable 13:

$$B_1 = \left(\frac{1}{M_1}\right)\left(A_{1_a}\tau_{11}\tau_{12}\ (1-\rho_1)G\ H_{1j11_a}\ H_{11_bm12}\right)$$

$$B_5 = \left(\frac{1}{M_5}\right)\left(A_5\tau_{10}(1-\rho_5)\{H_{5m10} + \tau_9^2 G\ H_{5m9_b}\ H_{9_a j 9_a}\ H_{9_b m10}\}\right)$$

$$B_6 = \left(\frac{1}{M_6}\right)\left(A_6\tau_{10}(1-\rho_6)\{H_{6m10} + \tau_9^2 G\ H_{6m9_b}\ H_{9_a j 9_a}\ H_{9_b m10}\}\right)$$

$$B_8 = \left(\frac{1}{M_8}\right)\left(A_{8_b}\tau_9\tau_{10}(1-\rho_{8_b})G\ H_{9_b m9_b}\ H_{8_b j 9_a} + A_{8_t}\tau_{10}(1-\rho_{8_t})\{H_{8_t m10}\right.$$

$$\left. + \tau_9^2 G\ H_{8_t m9_b}\ H_{9_a j 9_a}\ H_{9_b m10}\}\right)$$

All other elements are zero.

Variable 14:

$b_1 = K_1 K_2 K_3 b_{10}/M_1$

$b_{10} = (K_1 b_{10} + n_{10})/M_{10} \rightarrow b_{10} = \dfrac{n_{10}}{(1-K_1)}$, $\qquad M_{10} = 1.$

All other b's are zero.

5.2 DYNAMIC SENSOR MODEL EQUATIONS

Collecting all the above variables into a matrix differential equation,

Without Filter Dome:

$$\dot{T} = AT + DT^4 + B_Q\dot{Q} + BE + b + e \quad (8)$$

$$v = \bar{C}_T\, T + \bar{C}_b\, b + n$$

With Filter Dome:

$$\dot{T} = AT + DT^4 + B_Q\dot{Q} + B_s\, E_s + B_L\, E_L + b + e \quad (9)$$

$$v = \bar{C}_T\, T + \bar{C}_b\, b + n$$

In the above equations (8) and (9),

Eq. (8): T, T^4, B_Q, B, b and e are the column vectors of 9th order.

A and D are 9 x 9 matrices.

Eq. (9): T, T^4, B_Q, B_s, B_L, b and e are the column vectors of 10th order.

A and D are 10 x 10 matrices.

5.3 COUNT CONVERSION ALGORITHMS FOR M/WFOV TOTAL AND SHORTWAVE INSTRUMENTS

A. Steady-State Linearization Algorithm

1. Wide and Medium Field-of-View Total Instruments

The algorithm contains two parts. First a table is generated off-line for each instrument. Using the dynamic model parameters computed, a table of gain and offset values is generated and stored. This table is updated as needed when new flight calibration data arrives. The second part operates on-line. As data from the instrument is recieved, it is processed by this portion of the algorithm to obtain the irradiance at the field-of-view.

For the medium and wide FOV instrument the dynamic model has the form

$$\begin{aligned} \dot{T} &= AT + DT^4 + B_Q\dot{Q}(T_2) + BE + b, \\ v &= \bar{C}_T T + \bar{C}_b b, \end{aligned} \tag{10}$$

where the notation T^4 designates the vector whose i^{th} component is T_i^4; i.e., the fourth power of the i^{th} component of the vector T. The matrices and vectors A, D, B_Q, B and b are computed as specified in the model equations.

The gain and offset values consist of elements of the form (E_{oi}, V_{oi}, γ_{oi}), i = 0, 1, . . ., N, where

$$E_{oi} = i\Delta E_o, \qquad i = 0, 1, \ldots, N. \tag{11}$$

$$V_{oi} = \begin{pmatrix} v_{oi} \\ T_{Boi} \\ T_{Foi} \\ T_{Hoi} \end{pmatrix}, \qquad \gamma_{oi} = \begin{pmatrix} \gamma_{vi} \\ \gamma_{Bi} \\ \gamma_{Fi} \\ \gamma_{Hi} \end{pmatrix}. \tag{12}$$

E_{oi} is computed by the above equation, while V_{oi} is obtained using the following algorithm using the function

$$f(T_o,E_o) = AT_o + DT_o^4 + BE_o + b \tag{13}$$

<u>Algorithm for generating the table of points (E_{oi}, V_{oi}, γ_{oi})</u>

1. Initalize: $E_o = i\Delta E_o$, $T_1 = T_{oi-1}$, $z_1 = 0$ (i=0 only),

   $k = 1$, $\alpha = 1$

2. Compute* ΔT_k, T_{k+1}

$$\Delta z_k = \frac{-1}{a_{22}} B_Q' (A + 4D\,\tilde{T}_k^3)^{-1} [f(T_k, E) + B_Q z_k]$$

$$\Delta T_k = -\alpha(A + 4D\,\tilde{T}_k^3)^{-1} [f(T_k, E_{oi}) + B_Q(z_k + \Delta z_k)]$$

$$z_{k+1} = z_k + \Delta z_k$$

$$T_{k+1} = T_k + \Delta T_k$$

*The prime " ' " denotes the transpose.

a_{22} is the (2,2) element of $(A + 4D\,\tilde{T}_k^3)^{-1}$

3. If $\sum_{j=1}^{n} |f_j(T_{k+1}, E_{oi}) + B_Q\, z_{k+1}| \geq \sum_j |f_j(T_k, E_{oi}) + B_Q\, z_k|$,

   Set $\alpha = 2\alpha/3$ and GO TO 2

4. If $\sum_{j=1}^{n} |f_j(T_{k+1}, E_{oi}) + B_Q\, z_{k+1}| \leq \varepsilon$, GO TO 7

5. $k = k + 1$

6. GO TO 2

7. $V_{oi} = C_T\, T_{k+1} + C_b\, b$

8. $\beta = -C_T(A + 4D\,\tilde{T}_{k+1}^3)^{-1}\, B$

   $\gamma_{oi} = \frac{1}{\beta' Q \beta}\, Q\, \beta$

9. Store E_{oi}, V_{oi}, γ_{oi}

10. If $i > N$, STOP

11. $i = i + 1$

12. GO TO 1.

The matrix $\tilde{T}_k^3$ is defined as follows

$$T_k^3 = \begin{pmatrix} T_{k1}^3 & 0 & 0 & \cdots & 0 \\ 0 & T_{k2}^3 & 0 & \cdots & 0 \\ \vdots & & & & 0 \\ 0 & 0 & 0 & \cdots & T_{kn}^3 \end{pmatrix},$$

where T_{ki} is the ith component of T_k. The algorithm generates the look-up table of gains and offsets off-line and stores them.

The processing of data for count conversion is performed by the on-line part of the algorithm. Let V be a measurement to be processed consisting of readings of counts (v), base temperature (T_B), field of view limiter temperature (T_F) and the copper heat sink temperature (T_H); i. e.,

$$V = \begin{pmatrix} v \\ T_B \\ T_F \\ T_H \end{pmatrix}$$

On-line Count Conversion Algorithm

1. Obtain the value of v_{oi} (table look-up) "closest" to v (i.e., $|v - v_{oi}|$ is minimum). Note: start research at the last v_{oi} used to minimize real time usage.

2. Compute estimates $\hat{E}$ of irradiance at FOV

$$\hat{E} = E_{oi} + \gamma_{oi}' \ (V - V_{oi})$$

$$= E_{oi} + \gamma_{vi} \ (v - v_{oi}) + \gamma_{Bi} \ (T_B - T_{Boi})$$

$$+ \gamma_{Fi} \ (T_F - T_{Foi}) + \gamma_{Hi} \ (T_H - T_{Hoi}) \qquad (14)$$

2. Wide and Medium FOV Short Wave Instruments

The algorithm for the short wave instruments is similar to the total channel's, and consists of generating a table of gains and offsets, and an on-line algorithm for processing data. It is important to note that to obtain the estimate of the short wave irradiance at the field of view, the algorithm uses the estimate of the total irradiance corresponding to the some time to account for the effects of long wave radiation on the short wave measurement.

The dynamic model of the medium and wide field of view short wave instruments has the form

$$\dot{T} = AT + DT^4 + B_Q \ \dot{Q}(T_2) + B_s \ E_s + B_1 \ E_1 + b$$

$$V = C_T \ T + C_b \ b$$

The table consists of elements (E_{si}, $\hat{E}_{tim}$, V_{oim}, γ_{oim}, β_{oim}) and uses the function

$$f(T, E_s, \hat{E}_t) = AT + DT^4 + (B_s - B_1)E_s + B_1 \ \hat{E}_t + b. \qquad (15)$$

Algorithm for Generating Table (Shortwave)

1. $\hat{E}_t = m\Delta\hat{E}_t$, $z_1 = 0$ (m = 0 only)

2. $E_s = i\Delta E_s$, $T_1 = T_{oi-1}$, $k = 1$, $\alpha = 1$

3. $\Delta z_k = \frac{-1}{a_{22}} B_Q' (A + 4D \tilde{T}_k^3)^{-1} [f(T_k, E_s, \hat{E}_t) + B_Q z_k]$

$z_{k+1} = z_k + \Delta z_k$

4. $\Delta T_k = -\alpha(A + 4D \tilde{T}_k^3)^{-1} [f(T_k, E_s, \hat{E}_t) + B_Q z_{k+1}]$

$T_{k+1} = T_k + \Delta T_k$

5. Set 2nd element of T_{k+1} to T_{2NOM}; i.e., $T_{k+1\ 2} = T_{2NOM}$

6. If $\sum_{j=1}^{n} |f_j(T_{k+1}, E_s, \hat{E}_t) + B_Q z_{k+1}| \geq \sum_{j=1}^{n} |f_j(T_k, E_s, \hat{E}_t) + B_Q z_k|$

Set $\alpha = 2\alpha/3$ and GO TO 4

7. If $\sum_{j=1}^{n} |f_j(T_{k+1}, E_s, \hat{E}_t) + B_Q z_{k+1}| \leq \varepsilon$, GO TO 10

8. $k = k + 1$

9. GO TO 3

10. $V_{oim} = C_T T_{k+1} + C_b b$

11. $\beta_{oim} = -C_T (A + 4D \tilde{T}_k^3)^{-1} B_1$

12. $\beta = -C_T \left(A + 4D\, \tilde{T}_k^3 \right)^{-1} (B_s - B_1)$

$\gamma_{oim} = \frac{1}{\beta' Q \beta} \; Q\, \beta$

13. Store E_s, $\hat{E}_t$, V_{oim}, γ_{oim}, β_{oim}

14. If $i \geq N$ GO TO 17

15. $i = i + 1$

16. GO TO 2

17. If $m \geq M$, STOP

18. $m = m + 1$

19. GO TO 1.

The table is thus generated by the algorithm given above. This algorithm is used off-line to obtain the gains and offsets used in the on-line part of the count conversion algorithm.

The processing of arriving "input" data from "flight" operations for count conversion may be performed by the on-line portion of the algorithm. Let V be a measurement of counts and base, FOV limiter and copper heat sink temperatures obtained from a short wave instrument; i. e.,

$$V = \begin{pmatrix} v \\ T_B \\ T_F \\ T_H \end{pmatrix}$$

Arriving data of this form is processed as shown below.

On-line Count Conversion Algorithm (Short Wave)

1. Round $\hat{E}$ to the closest value of $\hat{E}_{tm}$. Note: $\hat{E}$ is the last output of the on-line count conversion algorithm for the appropriate total channel. Let m be the index of the rounded value $\hat{E}_{tm}$.

2. Obtain the value of v_{oim} (table look-up) closest to v; i.e., $|v - v_{oim}|$ is minimum for i = 0, i, . . ., N. Note: m is fixed by 1; start search at last value of v_{oim} used.

3. Compute estimate of irradiance at field of view aperture $\hat{E}_s$, $\hat{E}_1$.

$$\hat{E}_s = \hat{E}_{si} + \gamma'_{oim}\left[(V - V_{oim}) - \beta_{oim}(\hat{E} - \hat{E}_{tm})\right]$$

$$\hat{E}_1 = \hat{E} - \hat{E}_s$$

The on-line count conversion algorithm thus provide estimates of the short wave, long wave and total radiation incident on the field of view aperture in "normal" operation. The model parameters and look-up tables will be updated as needed when calibration data is obtained to account for changes in the instrument behavior.

B. Modified Kalman Filtering Algorithms

1. Medium and Wide FOV Total Instruments

The Steady State Linearization algorithms given are based on the assumption that temporal and spatial variations in the incoming radiance are sufficiently slow and small so that the output of the instrument is mainly determined by its steady state response. The algorithms presented in this section are based on concepts used in Kalman filtering and do not make this assumption so that the portion of the output due to the transient response is accounted for in the conversion. Further error reducing properties of these algorithms make them suitable for high accuracy measurements.

The algorithm is recursive and consists of the following equations given in matrix form.

$$\nu(t_k) = V(t_k) - C_T \bar{T}(t_k) - C_b\, b \tag{16a}$$

$$\hat{T}(t_k) = \bar{T}(t_k) + G_T\, \nu(t_k) \tag{16b}$$

$$\hat{E}(t_k) = \hat{E}(T_{k-1}) + \Delta t\, \hat{S}(t_{k-1}) + G_E\, \nu(t_k) \tag{16c}$$

$$\hat{S}(t_k) = \hat{S}(t_{k-1}) + G_s\, \nu(t_k) \tag{16d}$$

$$\bar{T}(t_{k+1}) = \phi\hat{T}(t_k) + \psi\hat{T}^4(t_k) + \Gamma_Q\, \dot{Q}(\hat{T}_2(t_k)) + \Gamma\hat{E}(t_k) + \theta\hat{S}(t_k) + (\psi b) \tag{16e}$$

where t_k is the k^{th} sampling instant, Δt the sampling interval, $V(t_k)$ the measurement vector at time t_k consisting of counts, base, FOV and heat sink temperature readings, and $\hat{E}(t_k)$ is the estimate of the irradiance incident on the FOV aperture at time t_k.

$$\dot{Q}(T_2(t_k)) = \begin{cases} q, & \text{if } \hat{T}_2(t_k) < T_{2NOM} - \varepsilon \text{ or } \{\hat{T}_2(t_k) < T_{2NOM} + \varepsilon \text{ and } \dot{Q}(\hat{T}_2(t_{k-1})) = q\} \\ o, & \text{otherwise} \end{cases}$$

The initial values of $\bar{T}(t_o)$, $\hat{E}(t_o)$ are obtained using the SSL algorithm for generating the look-up table, and $\hat{S}(t_o) = 0$.

2. Medium and Wide FOV Short Wave Instruments

The algorithm for the short wave instruments uses the estimate $E(t_k)$ and $S(t_k)$ obtained from the algorithm for the total channels. This allows the algorithm to estimate effects such as the heating of the dome filter and leakage.

$$\nu(t_k) = V(t_k) - C_T \, \bar{T}(t_k) - C_b \, b \tag{17a}$$

$$\hat{T}(t_k) = \bar{T}(t_k) + G_T \, \nu(t_k) \tag{17b}$$

$$\hat{E}_s(t_k) = \hat{E}_s(t_{k-1}) + \Delta t \, \hat{S}_s(t_{k-1}) + G_E \, \nu(t_k) \tag{17c}$$

$$\hat{S}_s(t_k) = \hat{S}_s(t_{k-1}) + G_S \, \nu(t_k) \tag{17d}$$

$$\bar{T}(t_{k+1}) = \phi\hat{T}(t_k) + \psi\hat{T}^4(t_k) + \Gamma_Q \, Q(\hat{T}_2(t_k)) + \Gamma_s \, \hat{E}_s(t_k) + \theta_s \, \hat{S}_s(t_k) + \Gamma_T \, \hat{E}(t_k) + \theta_T \, \hat{S}(t_k) + \psi b \tag{17e}$$

$\hat{E}_s(t_k)$ is the estimate of the short wave irradiance incident on the FOV aperture at time t_k.

NON-SCANNER DYNAMIC MODEL

NODES

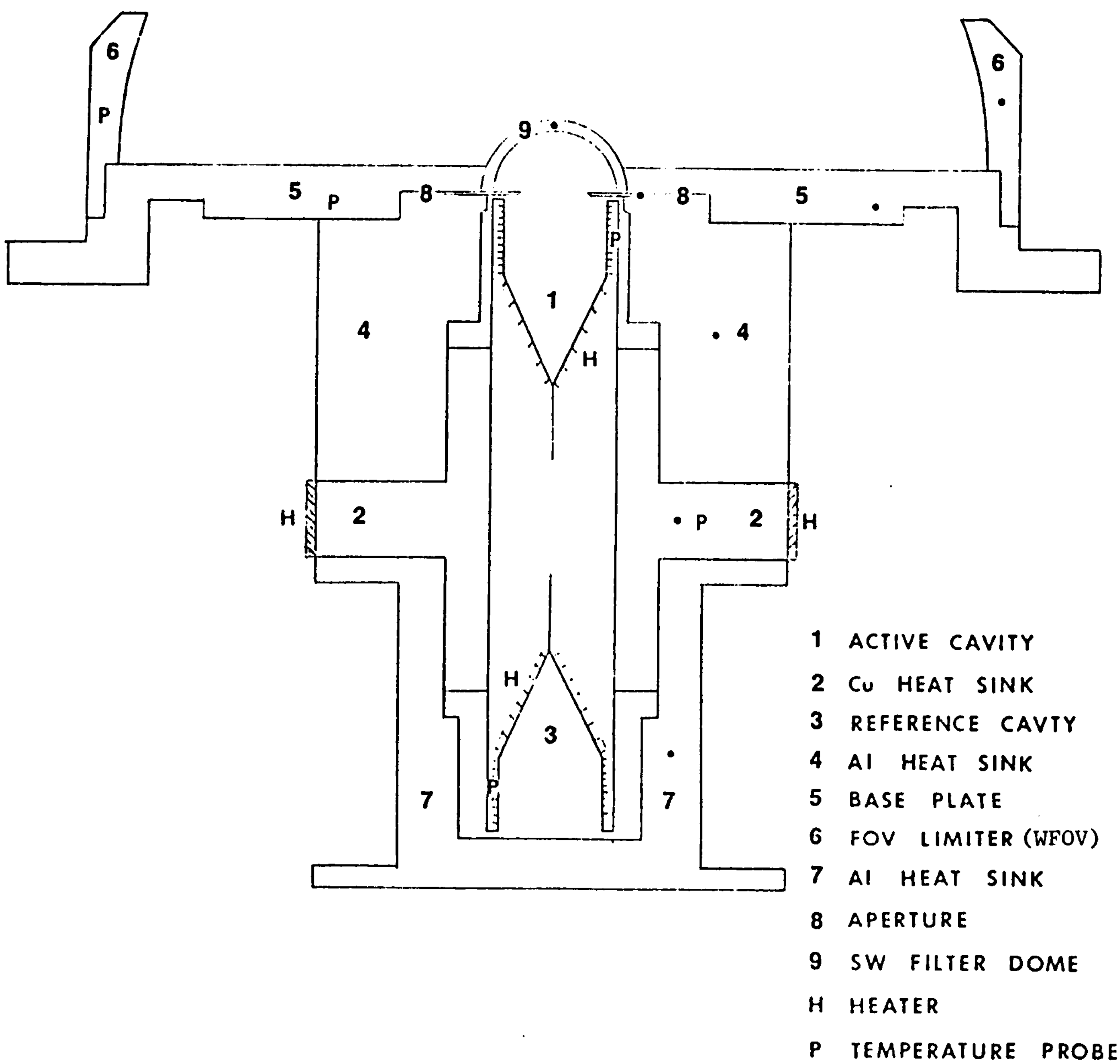

Figure 1

ACR CONTROL ELECTRONICS

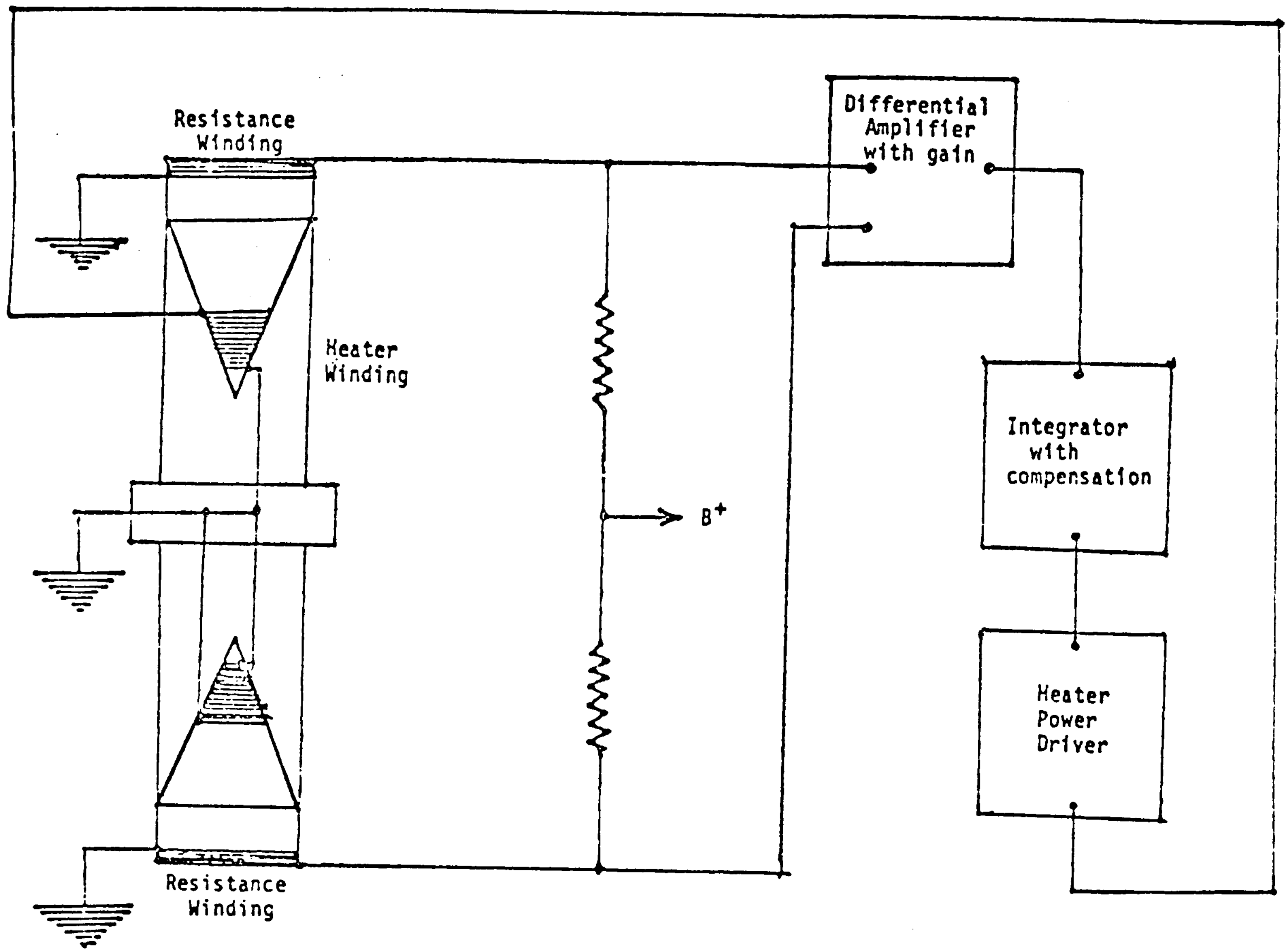

Figure 2

ELECTRONICS BLOCK DIAGRAM

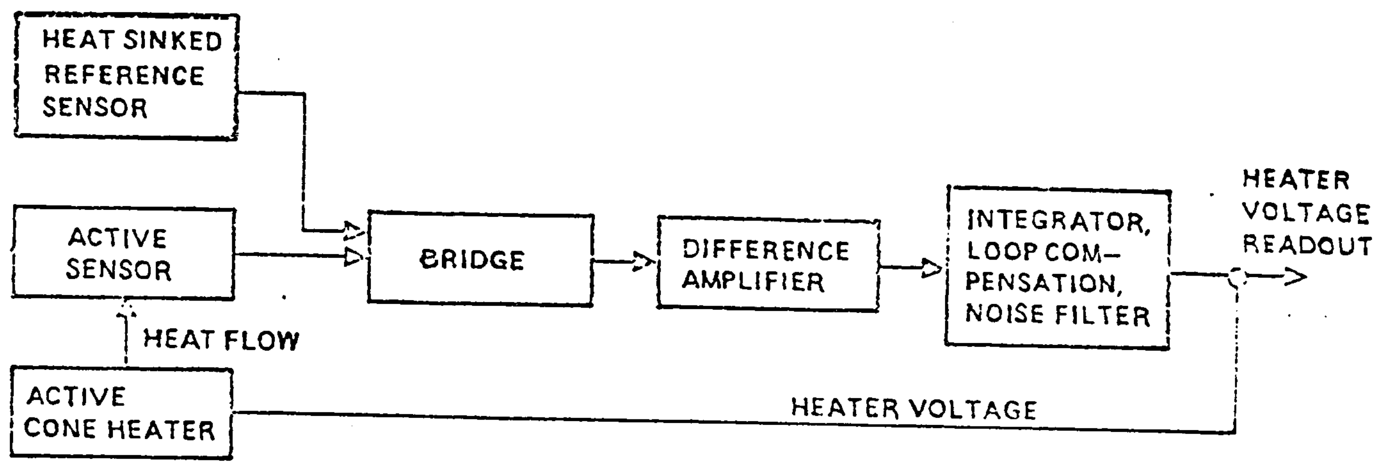

Figure 3

FUNCTIONAL FLOW DIAGRAM FOR SENSOR

CHARACTERIZATION AND CALIBRATION

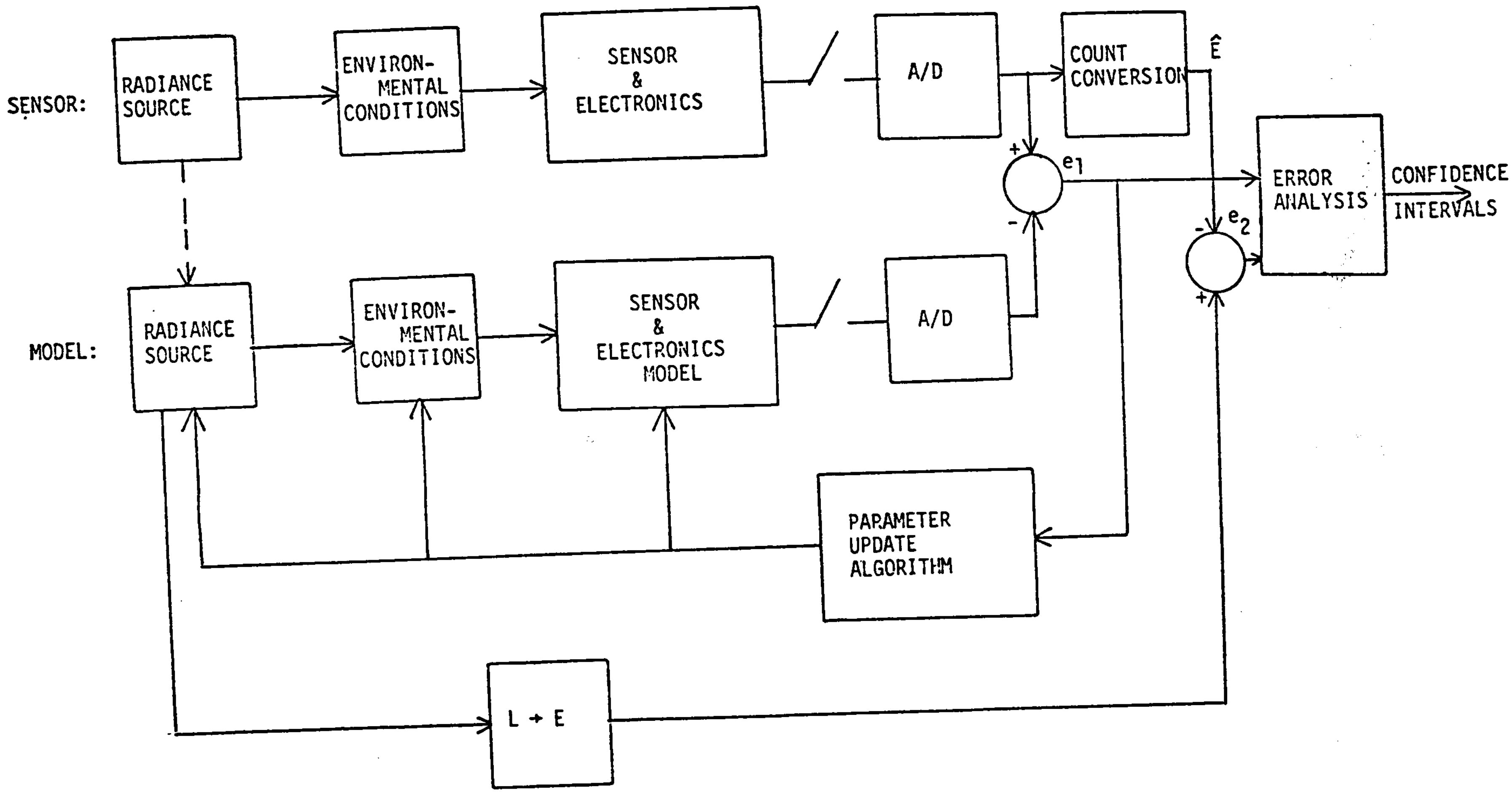

Figure 4

PRE/POST LAUNCH CALIBRATIONS

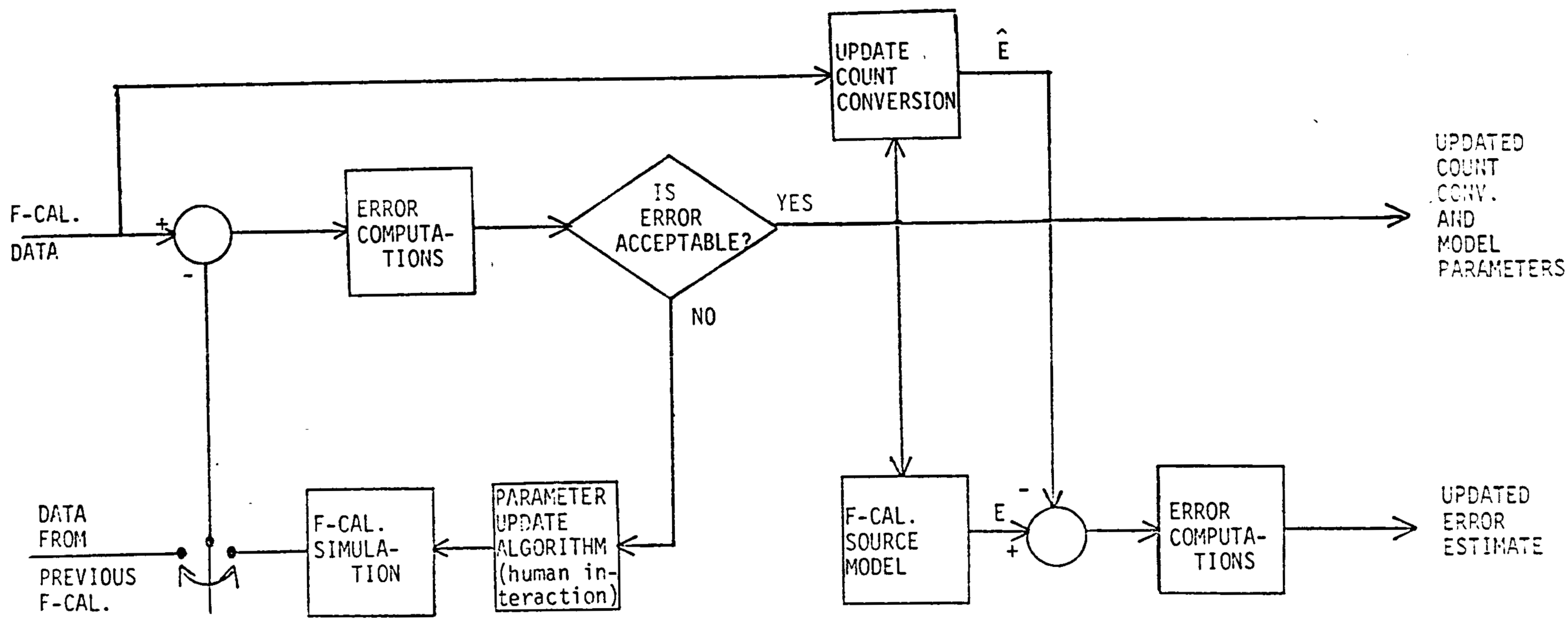

Figure 5

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INFLIGHT MEASUREMENTS

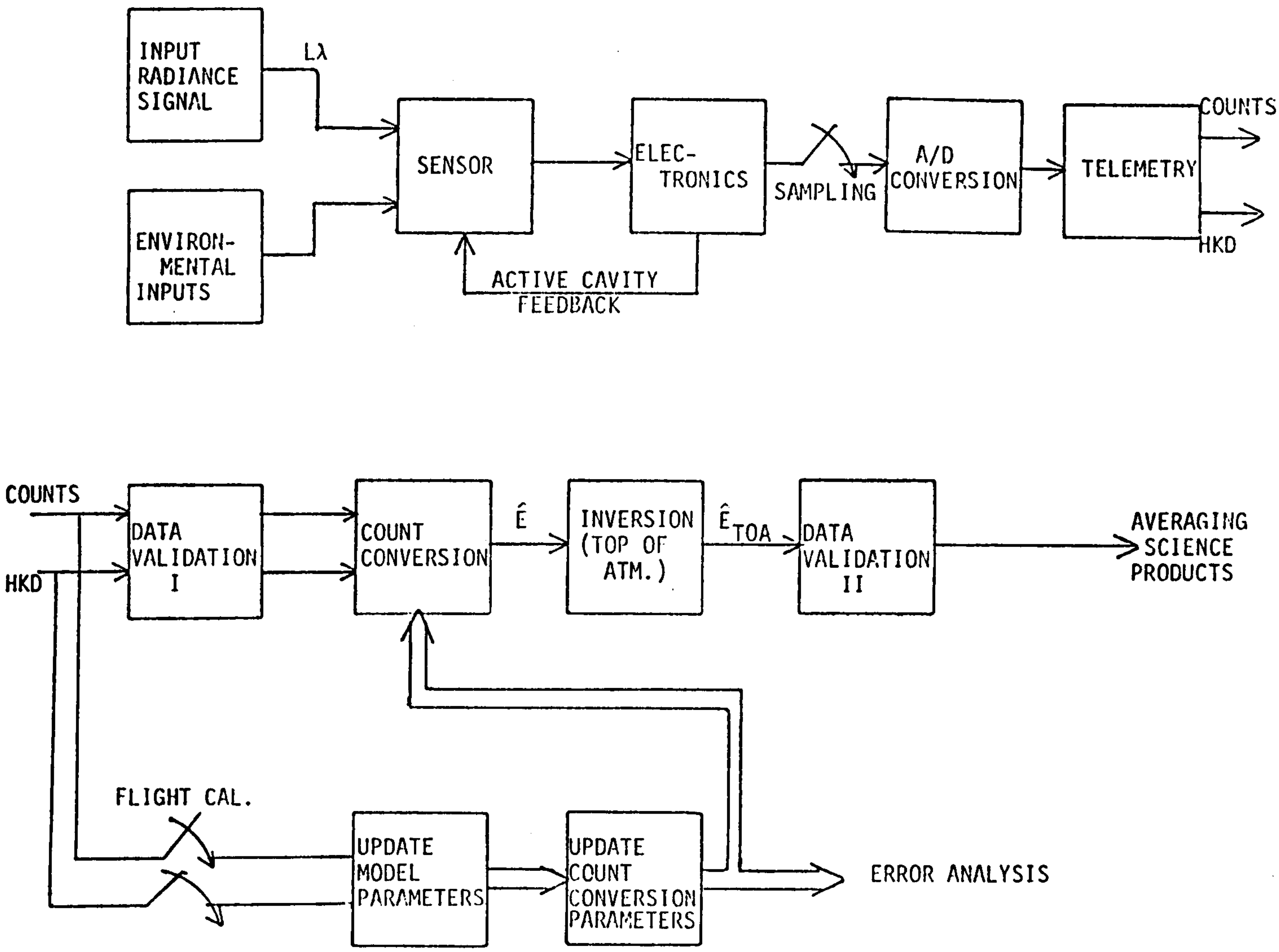


Figure 6

NONSCANNER THERMAL MODEL - WFOVSW

(see List of Subscripts, p. vi, for explanation of nomenclature)

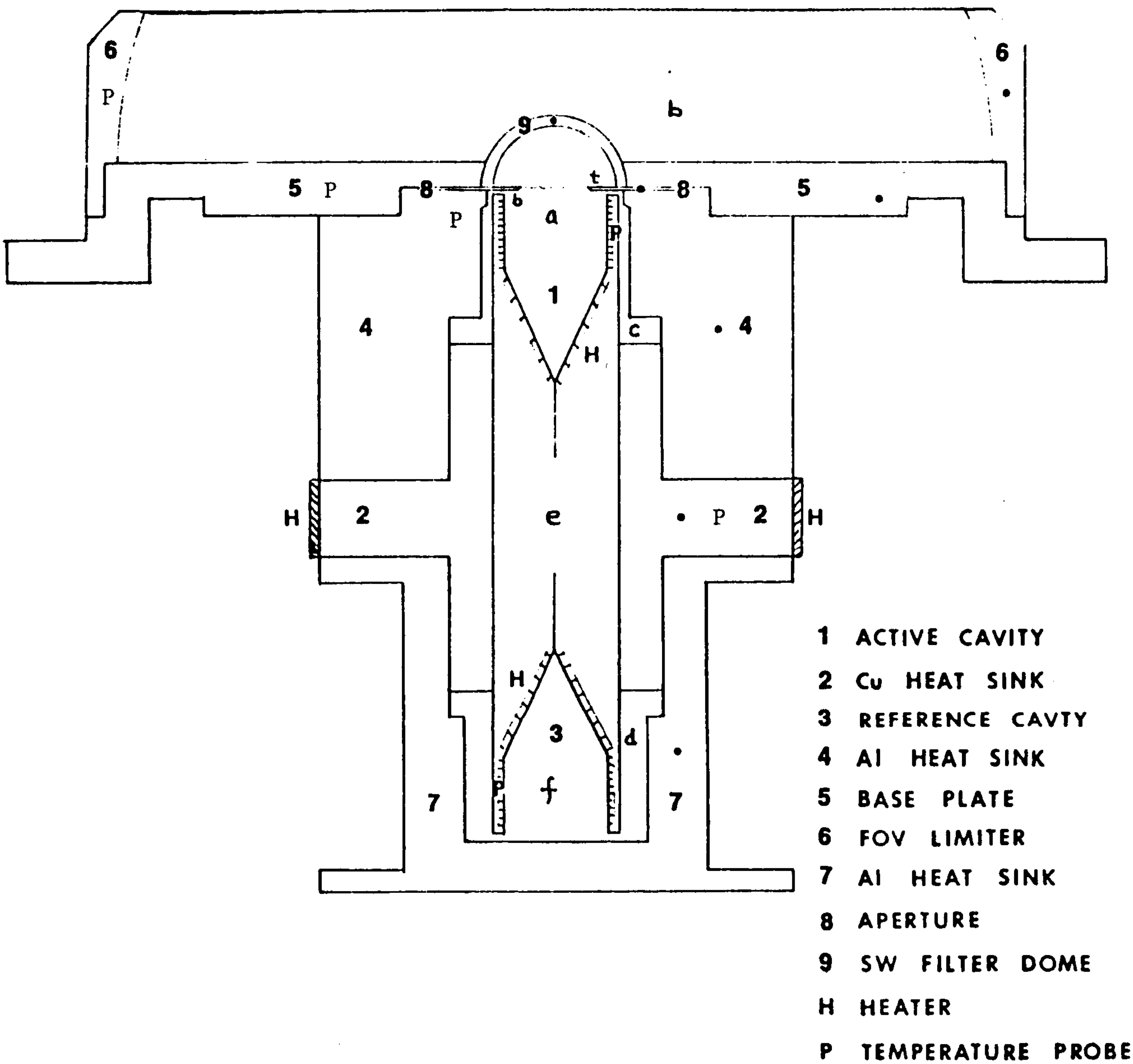
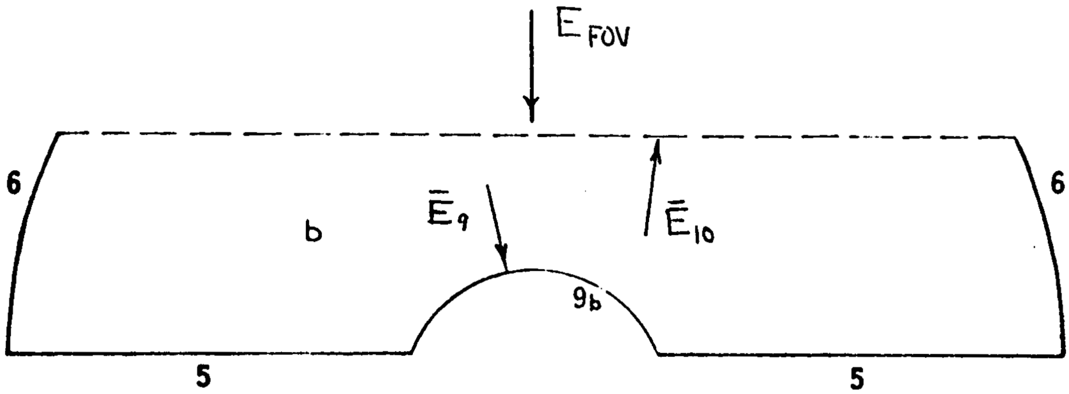


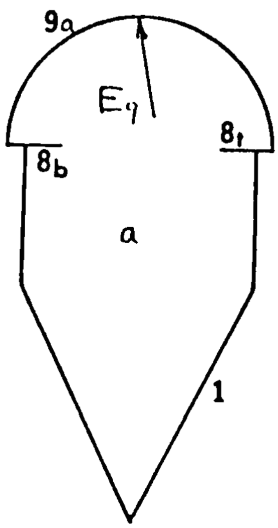
Figure 7

NONSCANNER WFOVSW ENCLOSURES

(see List of Subscripts, p. vi, for explantation of nomenclature)



FOV LIMITER ENCLOSURE, b



CAVITY ENCLOSURE, a

Figure 8

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Final Report

16. Abstract

This document defines two count conversion algorithms and the associated dynamic sensor model for the M/WFOV nonscanner radiometers. The sensor model provides and updates the constants necessary for the conversion algorithms, though the frequency with which these updates were needed was uncertain. This analysis therefore develops mathematical models for the conversion of irradiance at the sensor field-of-view (FOV) limiter into data counts, derives from this model two algorithms for the conversion of data counts to irradiance at the sensor FOV aperture and develops measurement models which account for a specific target source together with a sensor. The resulting algorithms are of the gain/offset and Kalman filter types. The gain/offset algorithm was chosen since it provided sufficient accuracy using simpler computations.

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