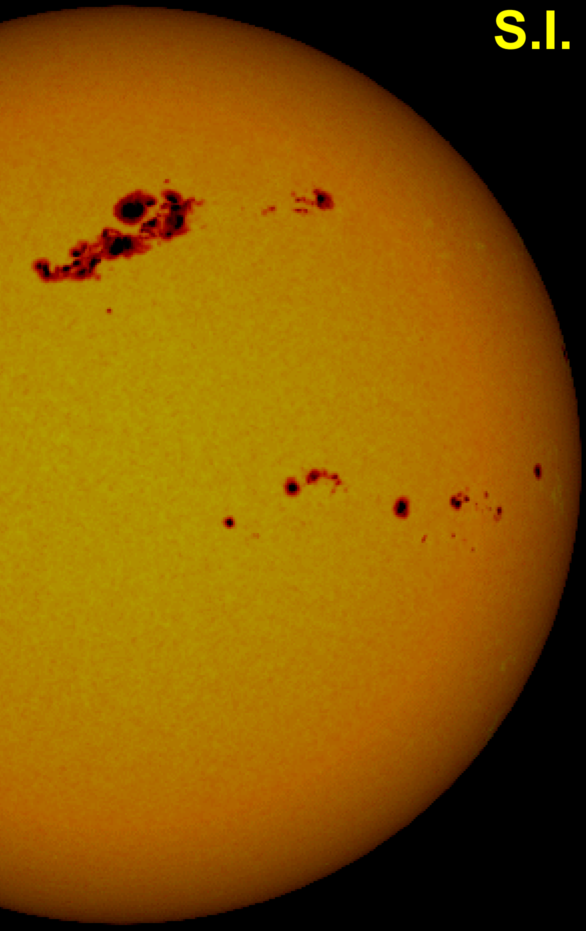
ACTIVE CAVITY RADIOMETER IRRADIANCE MONITORS 1,2 & 3
S.I. MEASUREMENT UNCERTAINTIES



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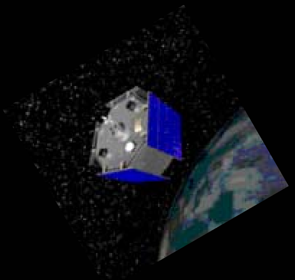
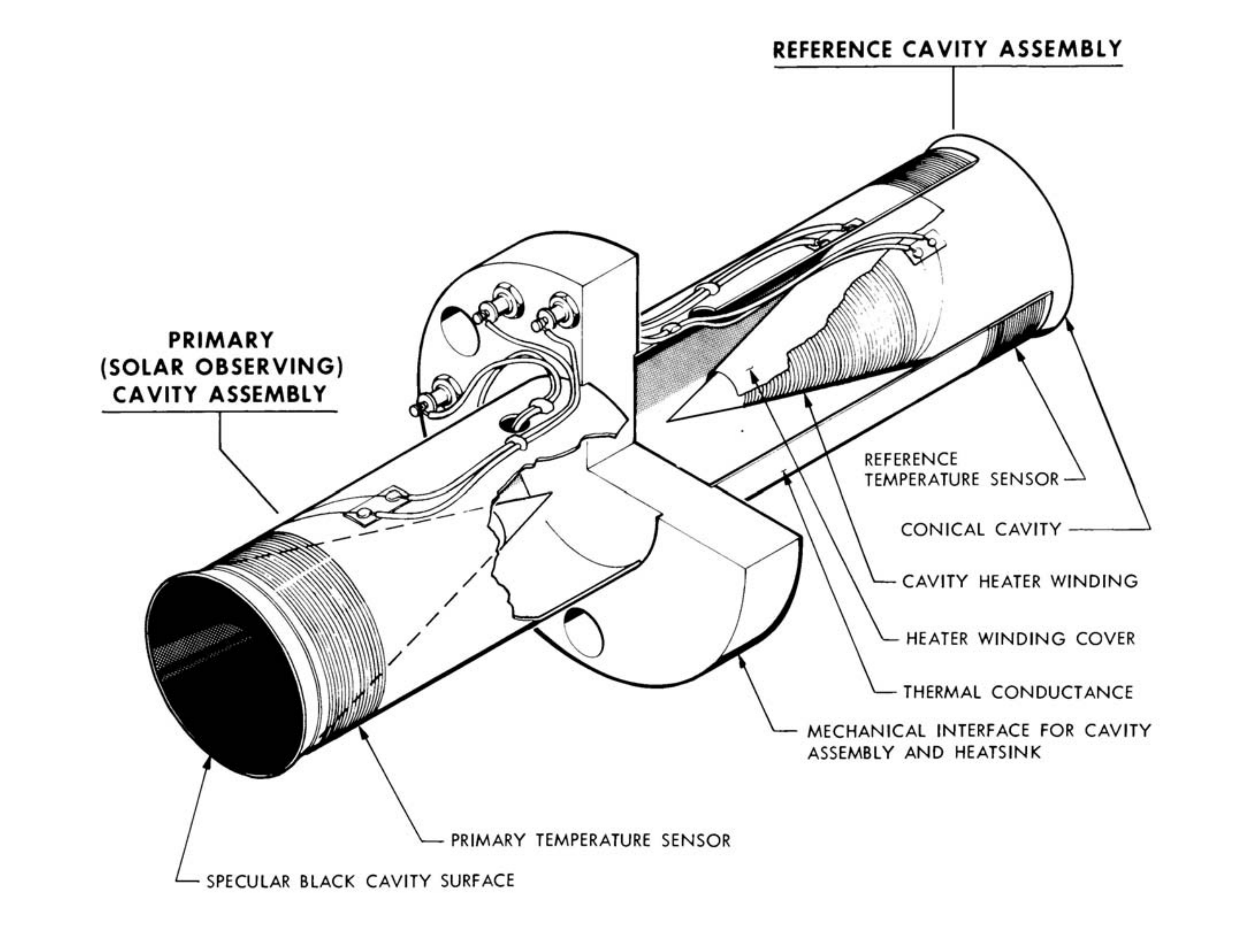
SMM/ACRIM1

UARS/ACRIM2

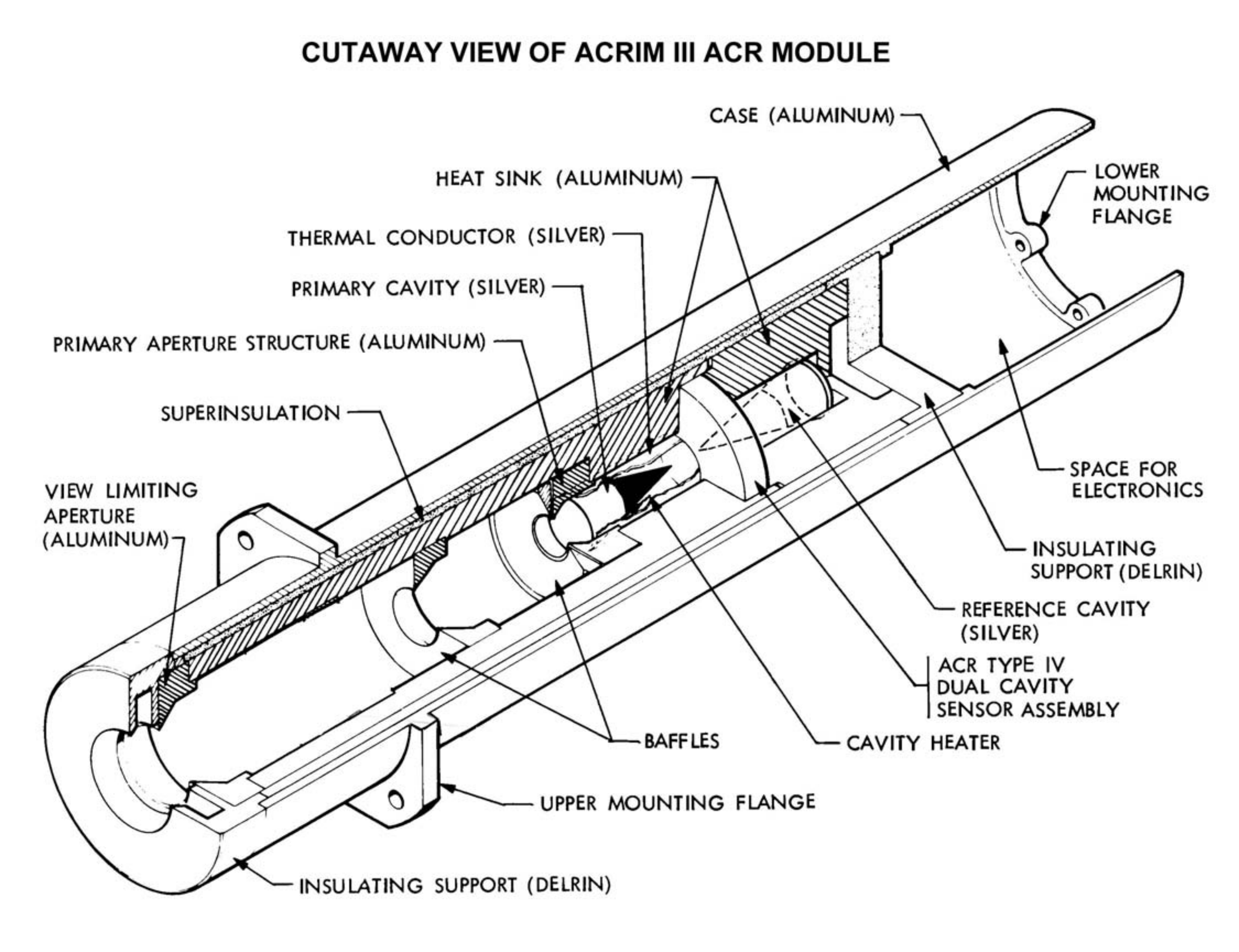


ACRIMSAT/ACRIM3

Active Cavity Radiometer Type 4



Active Cavity Radiometer Sensor Module



Active Cavity Radiometer measurements

- **Discussion of the Active Cavity Radiometer design**

The ACR employs differential operation

Irradiance measurements depend only differences in the thermal state of the cavity and its surround between reference and observation phases of measurement

ACR design concept is to maximize thermodynamic equivalence of the cavity in reference and observation phases by minimizing the effects of the many small temperature dependent terms.

ACR design concept is to minimize thermal drifting without active controls.

Studies of temperature drift effects, using characteristic values of the radiometer parameters and heat transfer modeling based on the above relationships, indicate temperature difference errors under most conditions are below the threshold of error defined by basic radiometer metrology.

Active Cavity Radiometer measurements

- **Basic properties of the Active Cavity Radiometer (ACR)**

Eq. 1 $$H = K\,(Per - Peo) + E$$

Where:

H = measured irradiance
K = standard detector constant of proportionality
Per = cavity electrical heater power in the reference mode
Peo = cavity electrical heater power in the observation mode
E = error terms (departures from quasi-equilibrium assumptions)

Axial rays undergo six reflections in the ACR cavity's specular, 30 deg. right circular cone the effective cavity absorptance is:

Eq. 2. $$\alpha c = 1 - \rho c^{6}$$

Where:

αc = effective cavity absorptance
ρc = absorptance of cavity surface
6 = number of reflections per axial ray

Active Cavity Radiometer measurements

- **Derivation of the ACR quasi-equilibrium equation**

In the reference phase (shutter closed) the input and output power to the cavity are:

Eq. 3. $Pinr = Per + \sum_j Prcr_j + Phcr$

Eq. 4. $Poutr = Pcr + \sum_j Pcrr_j + Plcr$

In the observation phase (shutter open) the input and output power to the cavity are:

Eq. 5. $Pino = Peo + H \bullet Ac \bullet (\alpha c + \rho \bullet \rho c) + \sum_j Prco_j + Phco$

Eq. 6. $Pouto = Pco + \sum_j Pcro_j + \Sigma_k Plco_k$

Where:

Pe = cavity electrical heating
Prc = radiative inputs to cavity from FOV j
Plc = loss by electrical lead conduction
H = Total Solar Irradiance
αc = effective cavity absorptance for TSI
ρc = effective cavity reflectance for TSI

Pcr = radiative outputs from cavity
Pc = loss by thermal conduction to the heatsink
Ac = Area of primary aperture
ρ = effective cavity FOV reflectance for TSI
Phc = input to cavity heat capacity

Active Cavity Radiometer measurements

The assumption of quasi-equilibrium requires that the sum of input and output power for the cavity in the reference and observations phases be nearly equal:

Eq. 7 $\sum Pinr \approx \sum Poutr$ (Reference phase)

Eq. 8 $\sum Pino \approx \sum Pouto$ (Observation phase)

Solving for the electrical heating powers using Eq.'s 2 – 8 and put the equation in the form of eq. 1:

Eq. 9

$H = 1/[Ac(\alpha c + \rho\rho c)]\ \{(Per - Peo)$	+	(electrical power term)
$C \cdot (Tdotr - Tdoto)$	+	(cavity heat capacity term)
$\sum_j (Pcrr_j - Pcro_j)$	-	(radiation from cavity term)
$\sum_j (Prcr_j - Prco_j)$	+	(radiation to cavity term)
$\sum_j (Pcr_j - Pco_j)$	+	(thermal conductance term)
$\sum_j (Plcr_j - Plco_j)\}$		(electrical lead conductance term)

Where: C = cavity heat capacity, Tdot = thermal drift rate of cavity

Active Cavity Radiometer measurements

- **Discussion of the quasi-equilibrium equation**

- **Reduction of differential temperature terms to negligible values closely approximates equilibrium conditions. In practical measurements use of the following equilibrium equation is justified:**

Eq. 10 $H = [A_c(\alpha c + \rho\rho c)]^{-1} \bullet \{(Per - Peo) + (Prcr_1 - Prco_1)\}$

Where:

$K = [A_c(\alpha c + \rho\rho c)]^{-1}$	Metrologically determined 'standard detector constant' of Eq. 1
Per – Peo	The difference in electrical substitution power supplied to maintain the same cavity thermal state in the reference and observation phases
$Prcr_1 - Prco_1$	The difference in radiative transfer to the cavity from its view limiting aperture (field of view 1) in the shutter open and closed phases

Active Cavity Radiometer measurements

- **Cavity heating power term (Per - Peo):**

Eq. 11 Per = Vr•Ir

Eq. 12 Peo = Vo•Io

Where:

> **Vr, Vo, Ir, Io are the cavity electrical heater voltages and currents in the shutter closed (reference) and shutter open (observations) phases of the measurement.**

- **Cavity heat capacity term:**

Eq. 13 C•(Tdotr - Tdoto)

Where:

> **This term represents the net power transferred to or from the heat capacity (C) of the cavity in the two phases of measurement.**

Active Cavity Radiometer measurements

- Radiation from the cavity to its surround $\sum_j (Pcrr_j – Pcro_j)$:

Eq. 14 $$\sum_j Pcr_j = \sum_j \varepsilon c_j \bullet Ac_j \bullet \sigma \bullet Tc_j^4 \bullet Fc_j$$

- Radiation to cavity from surround term $\sum_j (Prcr_j – Prco_j)$:

Eq. 15 $$\sum_j Prc_j = \sum_j \varepsilon_j \bullet Ac_j \bullet \sigma \bullet T_j^4 \bullet Fc_j$$

Where:

εc_j = cavity infrared (IR) emittance to j^{th} field of view (FOV)
ε_j = infrared (IR) emittance of j^{th} FOV
Ac_j = cavity area presented to j^{th} FOV
σ = Stefan-Boltzmann constant
Tc_j = temperature of cavity seen by j^{th} FOV
T_j = temperature of j^{th} FOV
Fc_j = radiative view factor between cavity and j^{th} FOV

Active Cavity Radiometer measurements

- **The 4π steradian FOV of the cavity has been subdivided into five regions for the analysis of functional relationships between the cavity and its surround:**

FOV Description

1 Cavity's view through its view limiting aperture (solar view)

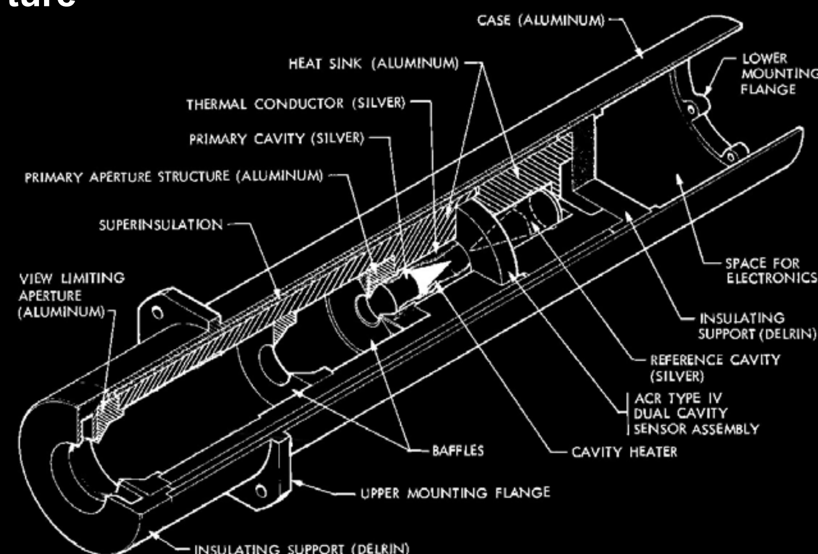
2 Cavity's view of the heat sink extension-view limiting assembly

3 Cavity's view of underside of primary aperture

4 Cavity's view of thermal impedance

5 Cavity's view of heat sink

CUTAWAY VIEW OF ACRIM III ACR MODULE



Active Cavity Radiometer measurements

- **Conductance to the heat sink from the cavity:**

Eq. 16 $Pc = Ktc \bullet (Tc - T_5)$

Where:

Ktc = thermal conductance from cavity to heatsink
Tc = cavity temperature
Ths = heatsink temperature

- **Conductance to heatsink through leads :**

Eq. 17 $\sum_k Plc_k = \sum_k Klc_k \bullet (Tc - T_5)$

Where:

Klc_k = thermal conductance of k^{th} electrical lead from cavity to heat sink

Active Cavity Radiometer measurements

SYMBOL	UNITS	VALUE	UNCERTAINTY	DESCRIPTION
αc	-	0.9995	0.000002	cavity absorptance
A_c	cm^2	0.500	0.0001	area of primary aperture
ρc	-	0.0005	0.0002	effective cavity reflectance for TSI
ρ	-	0.05	0.01	reflectance of cavity's FOV for TSI
Vo	volts	3.75	0.00015	cavity heater voltage - shutter open
Vr	volts	7.5	0.00015	cavity heater voltage - shutter closed
Io	amps	0.008	0.00015	cavity heater current - shutter open
Ir	amps	0.013	0.00015	cavity heater current - shutter closed
Kth	mW/K	100	0.4	thermal impedance conductance
Klc_k	mW/K	0.1	0.01	cavity electrical lead conductance
σ	$mW\text{-}cm^{-2}\text{-} K^{-4}$	5.6697×10^{-12}	7×10^{-16}	Stefan-Boltzmann constant
C	$mW\text{-}sec\text{-}K^{-1}$	500	10	cavity heat capacity
$\varepsilon_{1,2,3}$	-	0.98	0.02	cavity emittance to FOV's 1,2,3
$\varepsilon_{4,5}$	-	0.05	0.05	cavity emittance to FOV's 4,5

Active Cavity Radiometer measurements

SYMBOL	UNITS	VALUE	UNCERTAINTY	DESCRIPTION
$Ac_{1,2}$	cm^2	0.5	0.00013	cavity areas seen by FOV's 1,2
Ac_3	cm^2	1.3	0.13	cavity areas seen by FOV 3
$Ac_{4,5}$	cm^2	5.0	0.2	cavity areas seen by FOV's 4,5
ε_1	-	0.05	0.02	emittance of FOV 1
$\varepsilon_{2,3}$	-	0.95	0.02	emittance of FOV's 2,3
$\varepsilon_{4,5}$	-	0.05	0.02	emittance of FOV's 4,5
Tc	K	300.5	2	cavity temperature
$T_{1,2,3,5}$	K	301	2	temperatures of FOV's 1,2,3,5
T_4	K	300.5	2	temperatures of FOV 4
δTc	K	0.01	-	cavity temperature drift per cycle
δT_1	K	10	-	FOV 1 temperature drift per cycle
$\delta T_{2,3,4,5}$	K	.1	-	FOV's 2,3,4,5 temp. drift per cycle
Fc_1	-	8×10^{-2}	5×10^{-4}	cavity view factor to FOV 1
Fc_2	-	0.923	6×10^{-5}	cavity view factor to FOV 2
Fc_3	-	0.704	5×10^{-2}	cavity view factor to FOV 3
Fc_4	-	0.8	0.08	cavity view factor to FOV 4
Fc_5	-	0.2	0.02	cavity view factor to FOV 5

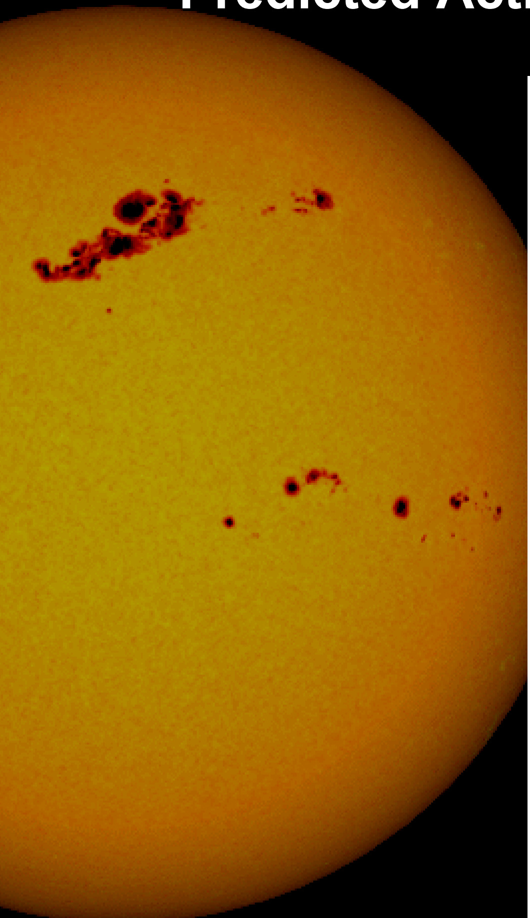
Active Cavity Radiometer Measurements

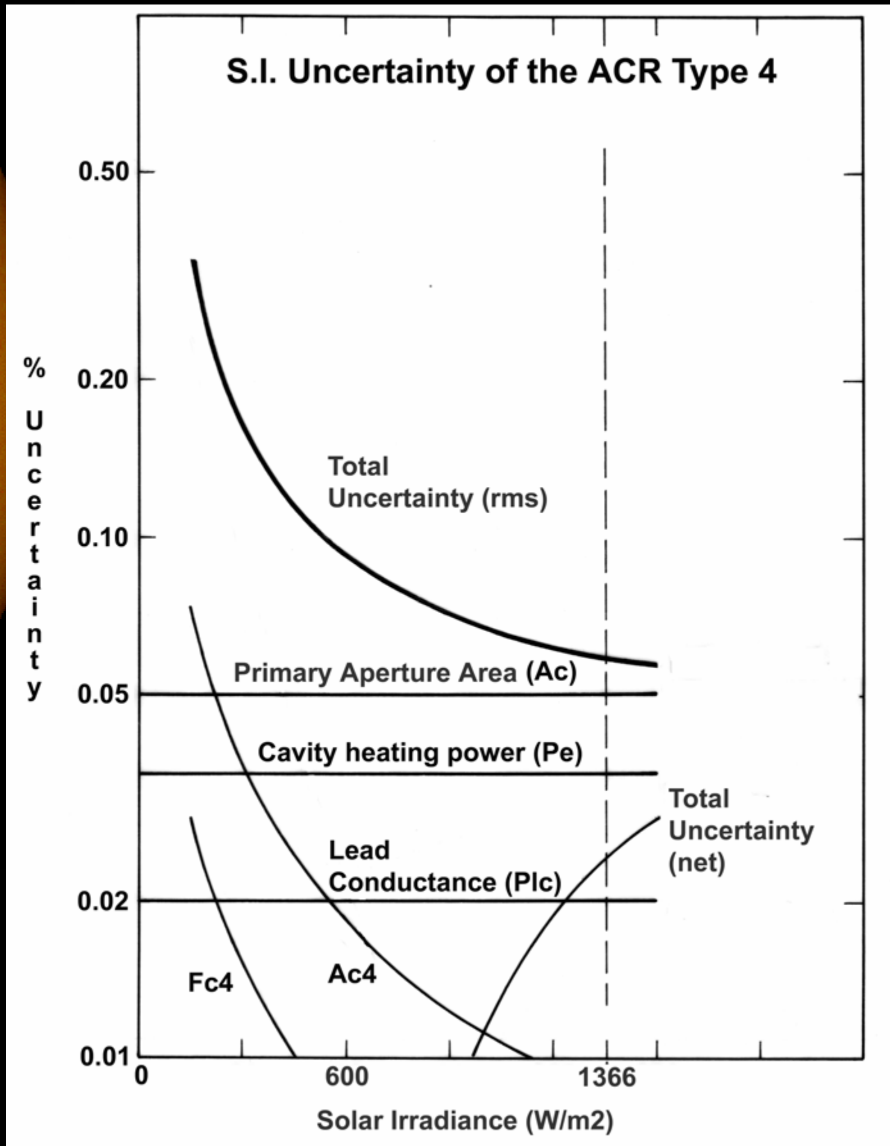
- ACRIM design based on passive realization of small measurement phase temperature differences
- To the extent this is achieved, the quasi-equilibrium equation (Eq. 9) can be simplified using Taylor expansions about reference phase temperatures:

Eq. 18

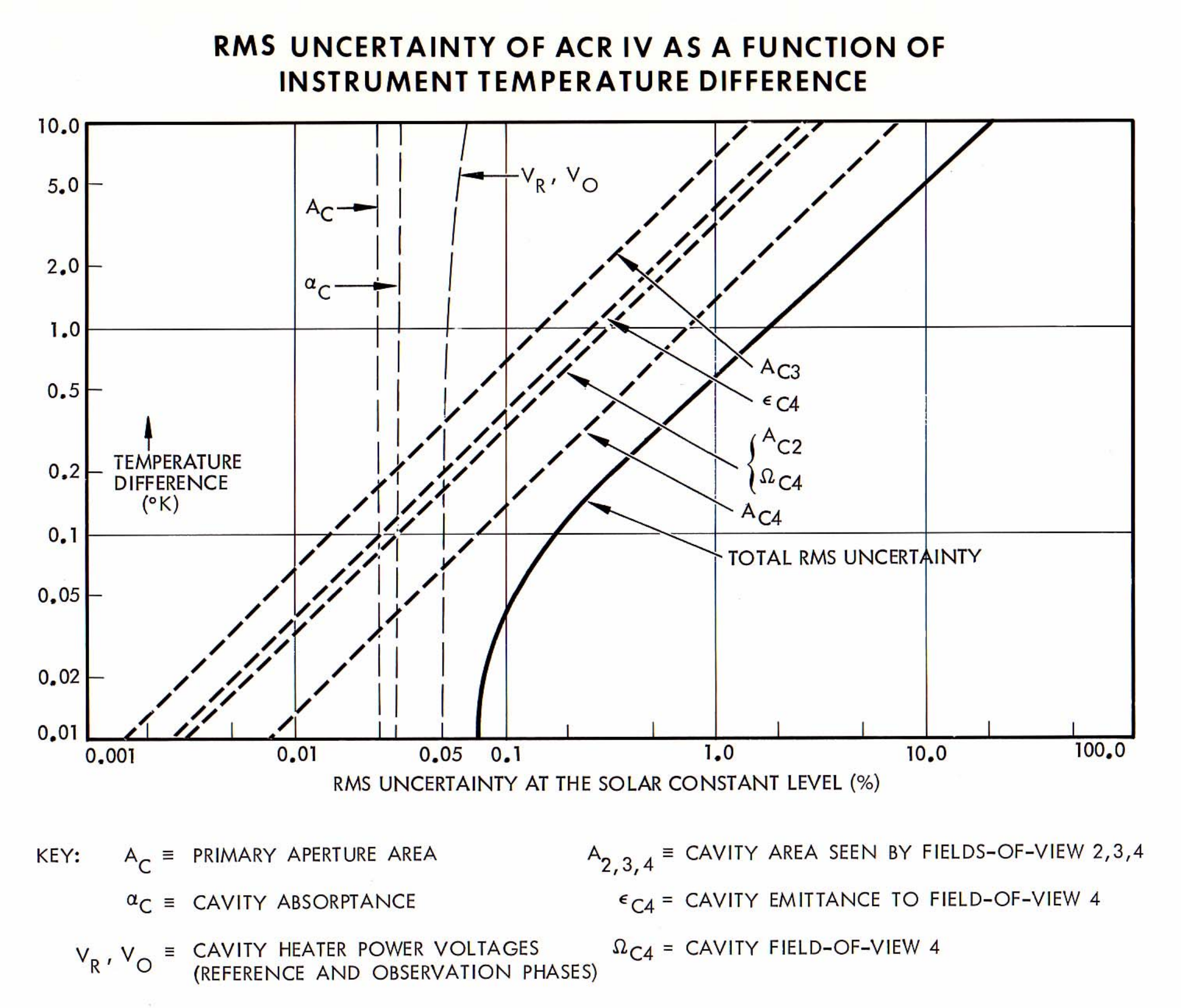
$H = 1/[Ac(\alpha c + \rho\rho c)]$ {(Per - Peo) +			(electrical power)
C•(Tdotr - Tdoto)	→	- C•δTdotr	(cavity heat capacity)
$\sum_j (Pcrr_j - Pcro_j)$	→	$- 4 \cdot \sigma \cdot \sum_j Ac_j \cdot Fc_j \cdot \varepsilon c_j \cdot Tcrr_j^3 \cdot \delta Tcrr_j$	(radiation from cavity)
$\sum_j (Prcr_j - Prco_j)$	→	$- 4 \cdot \sigma \cdot \sum_j Ac_j \cdot Fc_j \cdot \varepsilon j \cdot Trcr_j^3 \cdot \delta Trcr_j$	(radiation to cavity)
(Pcr - Pco)	→	- Ktc•(δTcr – δT5r)	(thermal conductance)
$\sum_k (Plcr_k - Plco_k)$}	→	$- \sum_k Klc_k \cdot (\delta Tcr - \delta T5r)$	(lead conductance)

Predicted Active Cavity Radiometer Uncertainties in S.I. Units

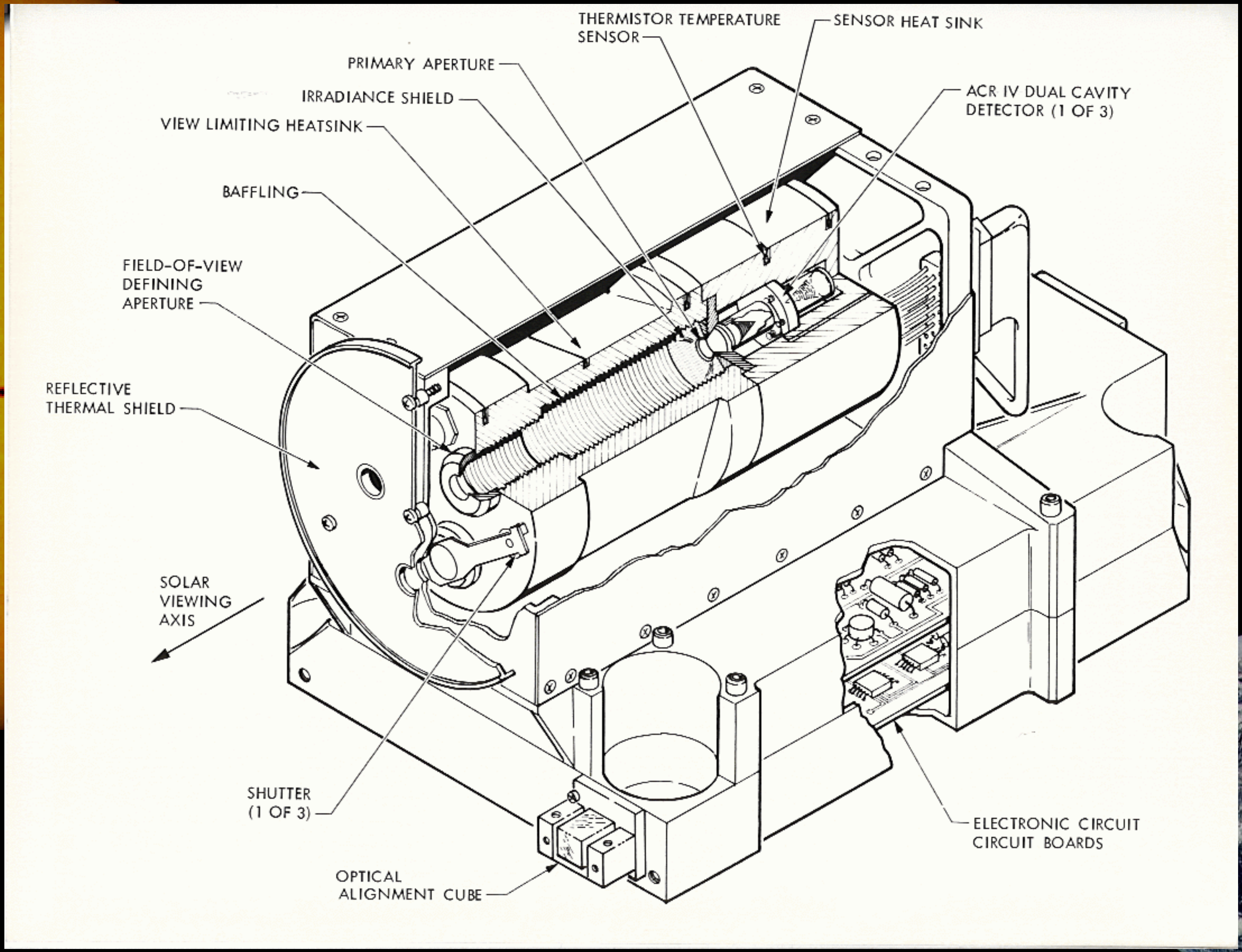




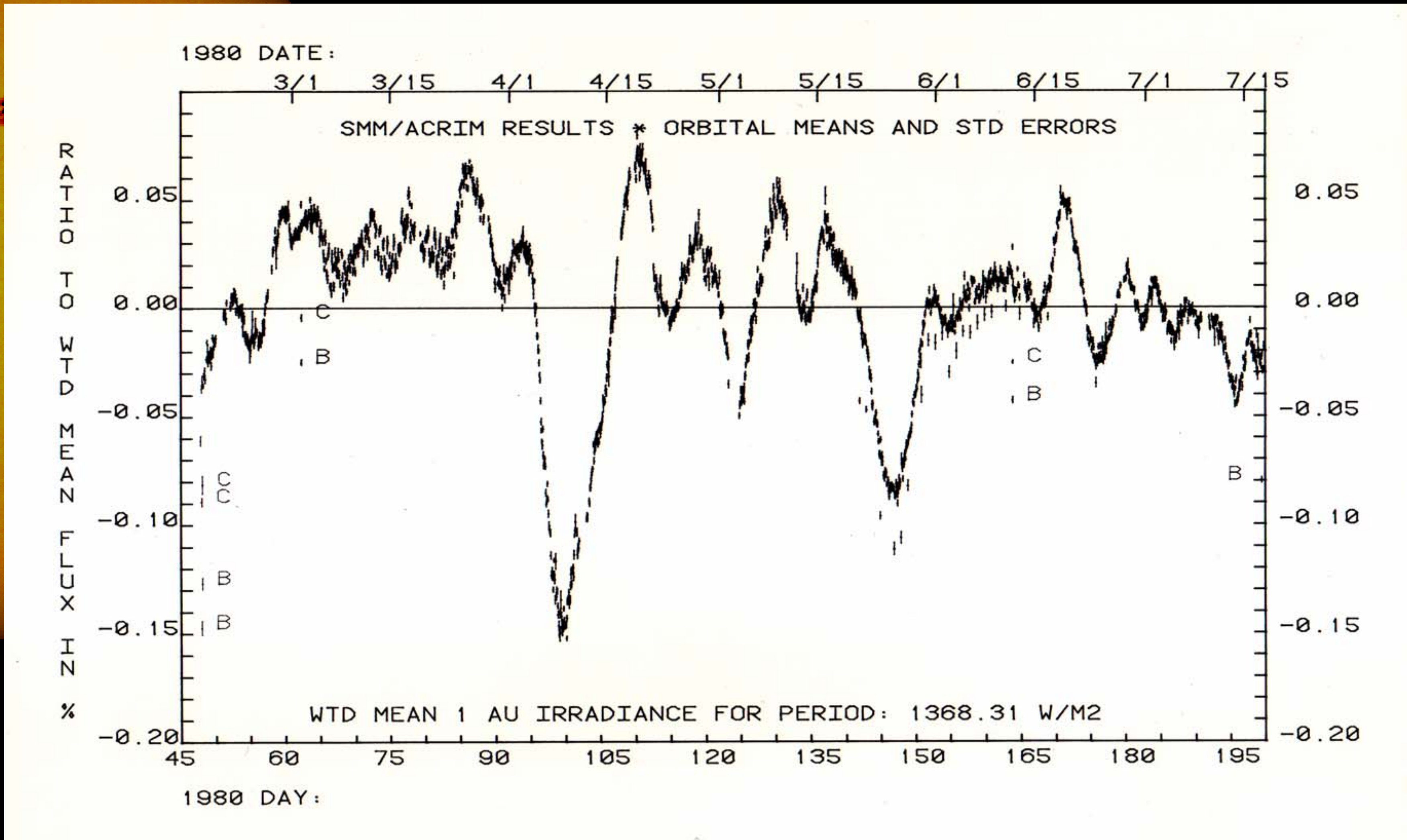
Predicted Active Cavity Radiometer Uncertainties caused by thermal drifting between measurement phases



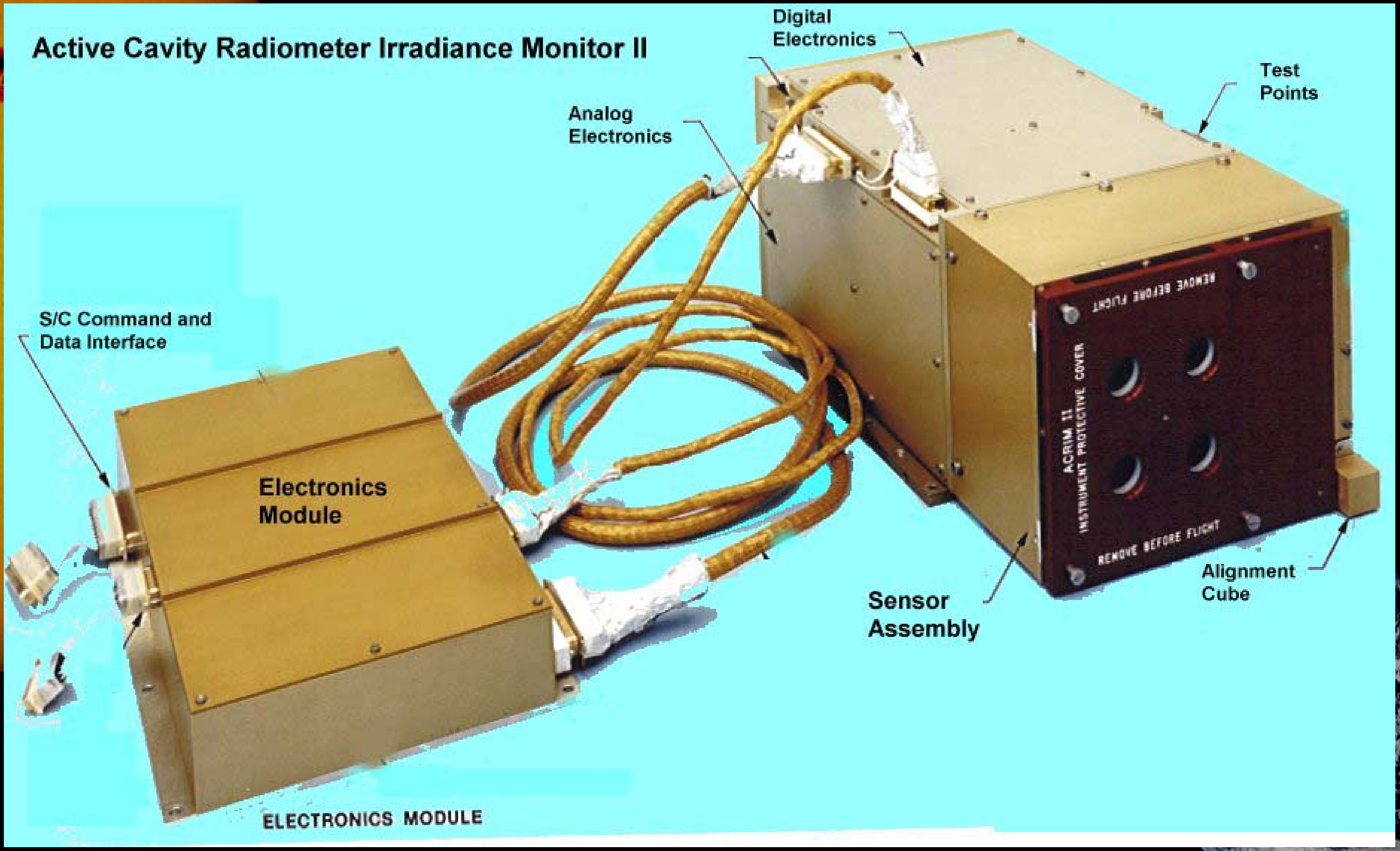
SMM/ACRIM1 Instrument



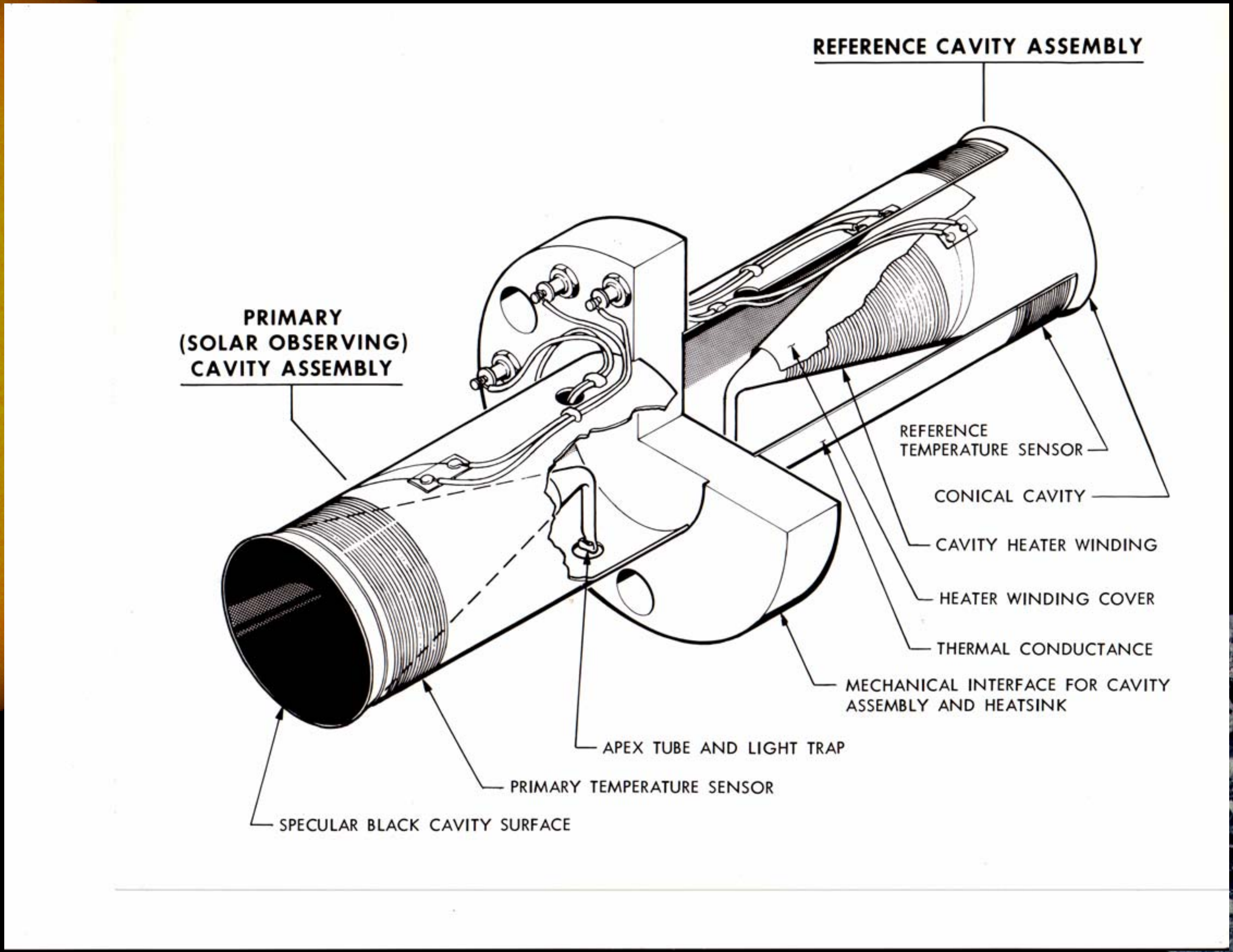
SMM/ACRIM1 Early Mission Comparisons



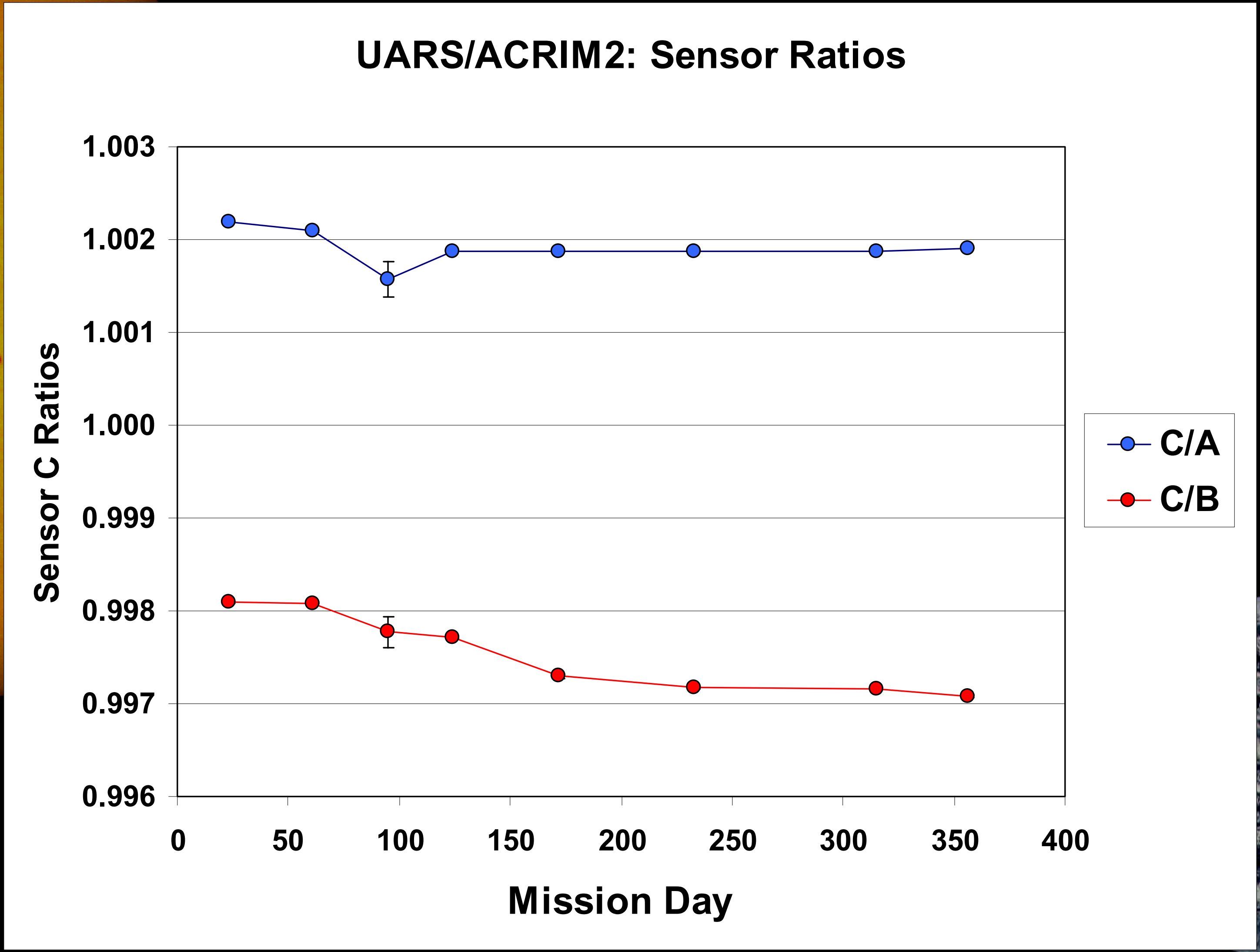
UARS/ACRIM2 Instrument



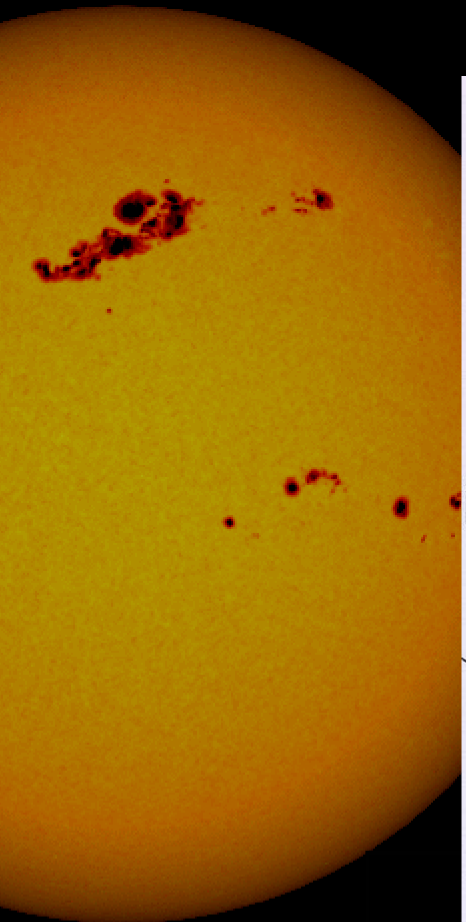
UARS/ACRIM2 ACR Type V Cavity

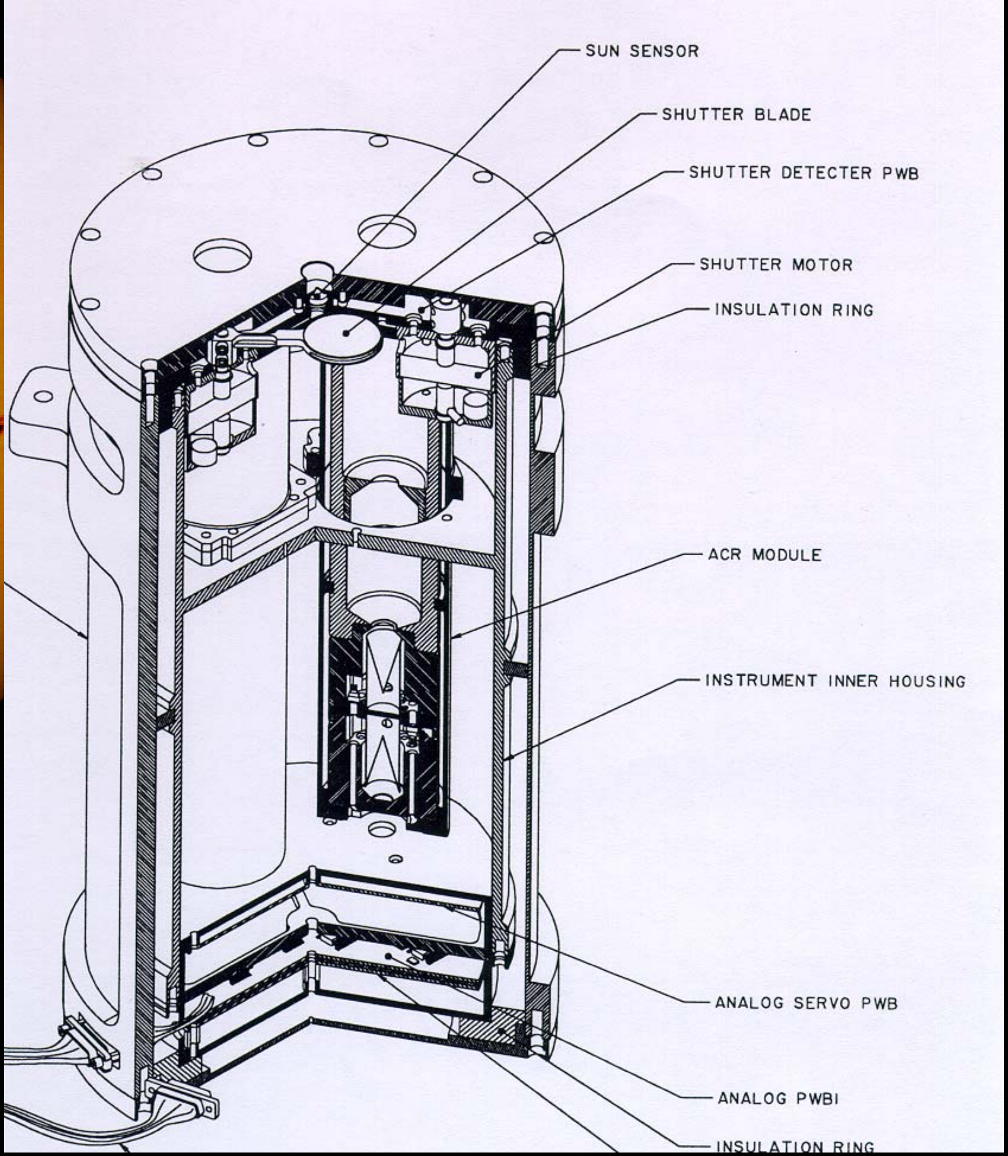


UARS/ACRIM2 Sensor Comparisons – 1st Year



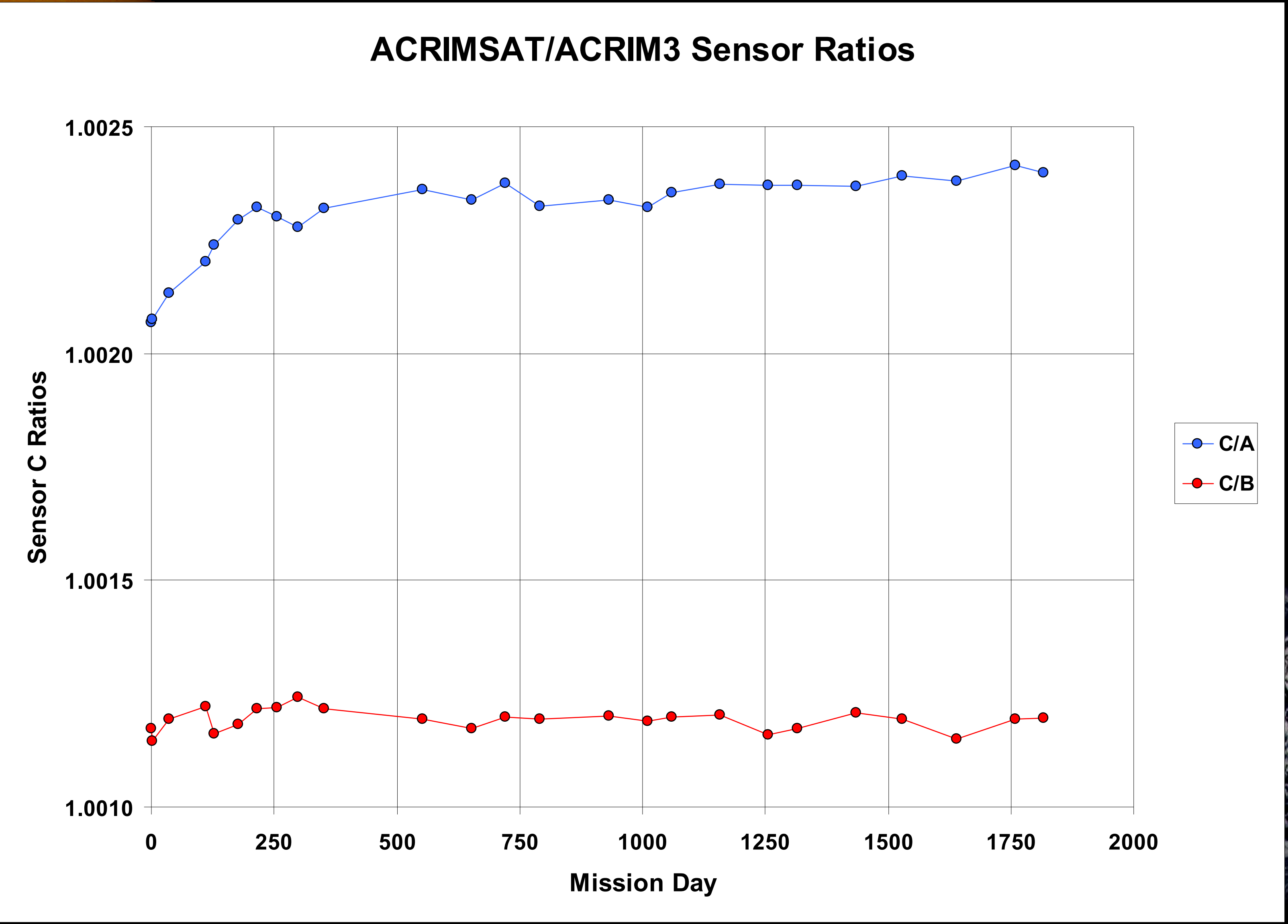
ACRIM3



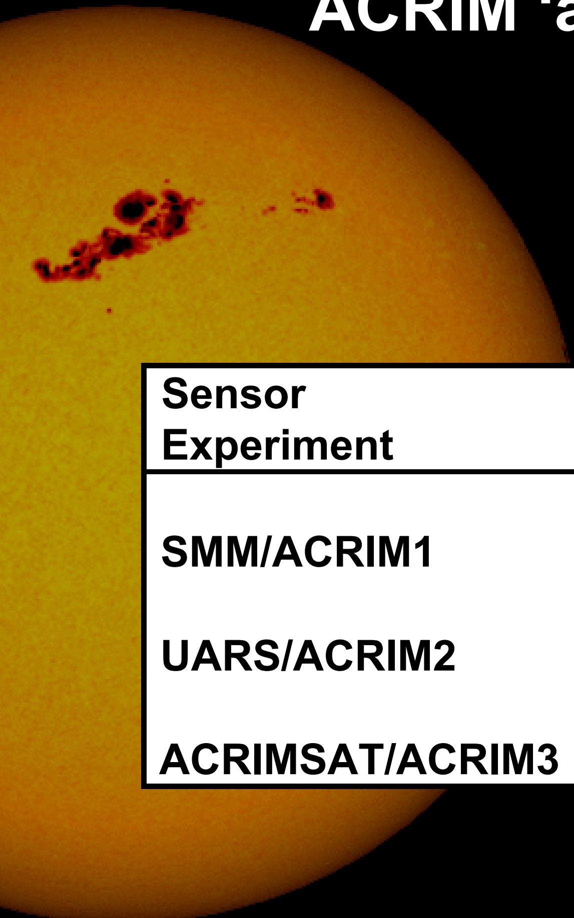


SUN SENSOR
SHUTTER BLADE
SHUTTER DETECTER PWB
SHUTTER MOTOR
INSULATION RING
ACR MODULE
INSTRUMENT INNER HOUSING
ANALOG SERVO PWB
ANALOG PWBI
INSULATION RING

ACRIM3 Comparisons and Degradation

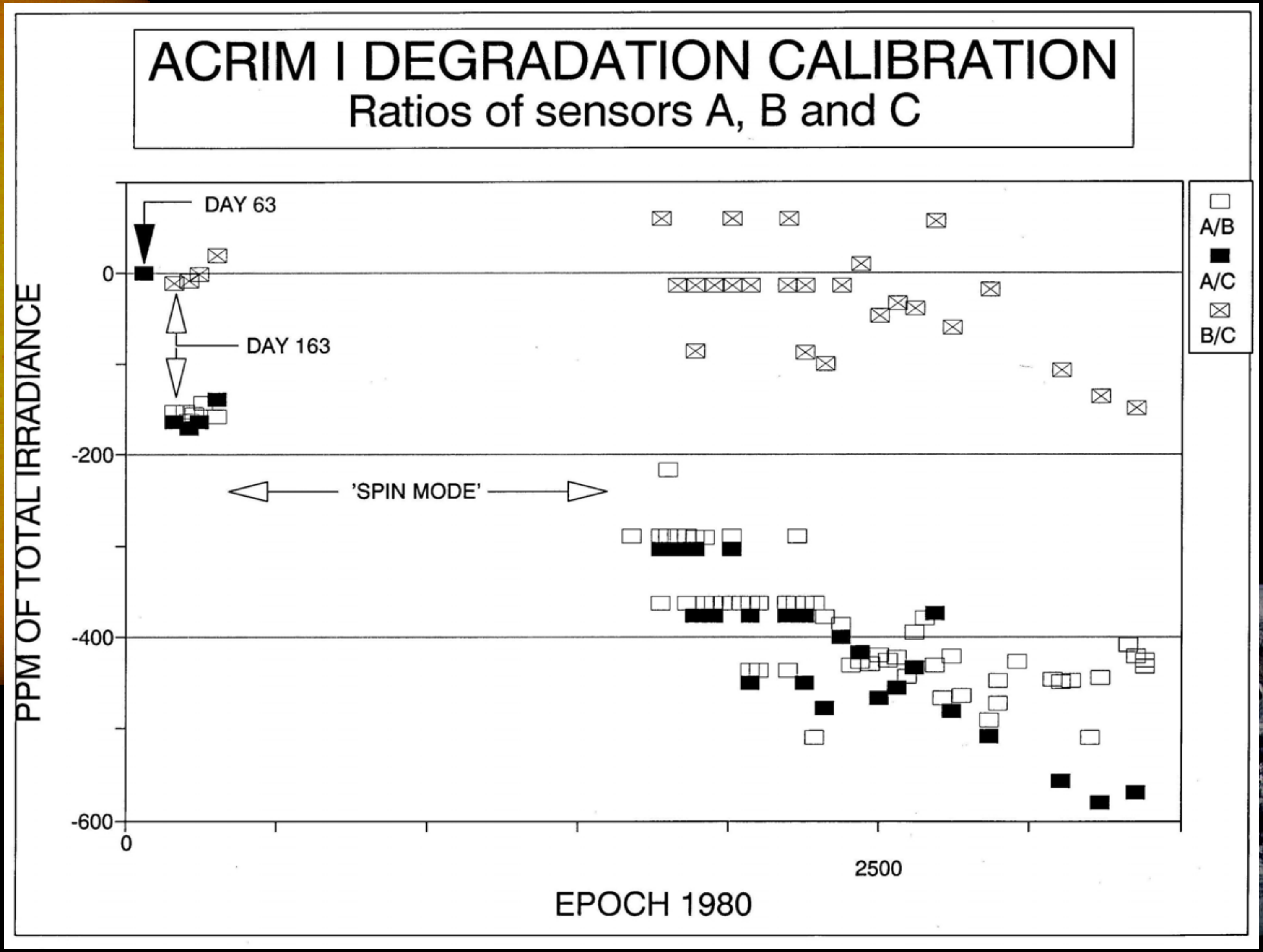


ACRIM 'as-launched' Sensor Comparisons

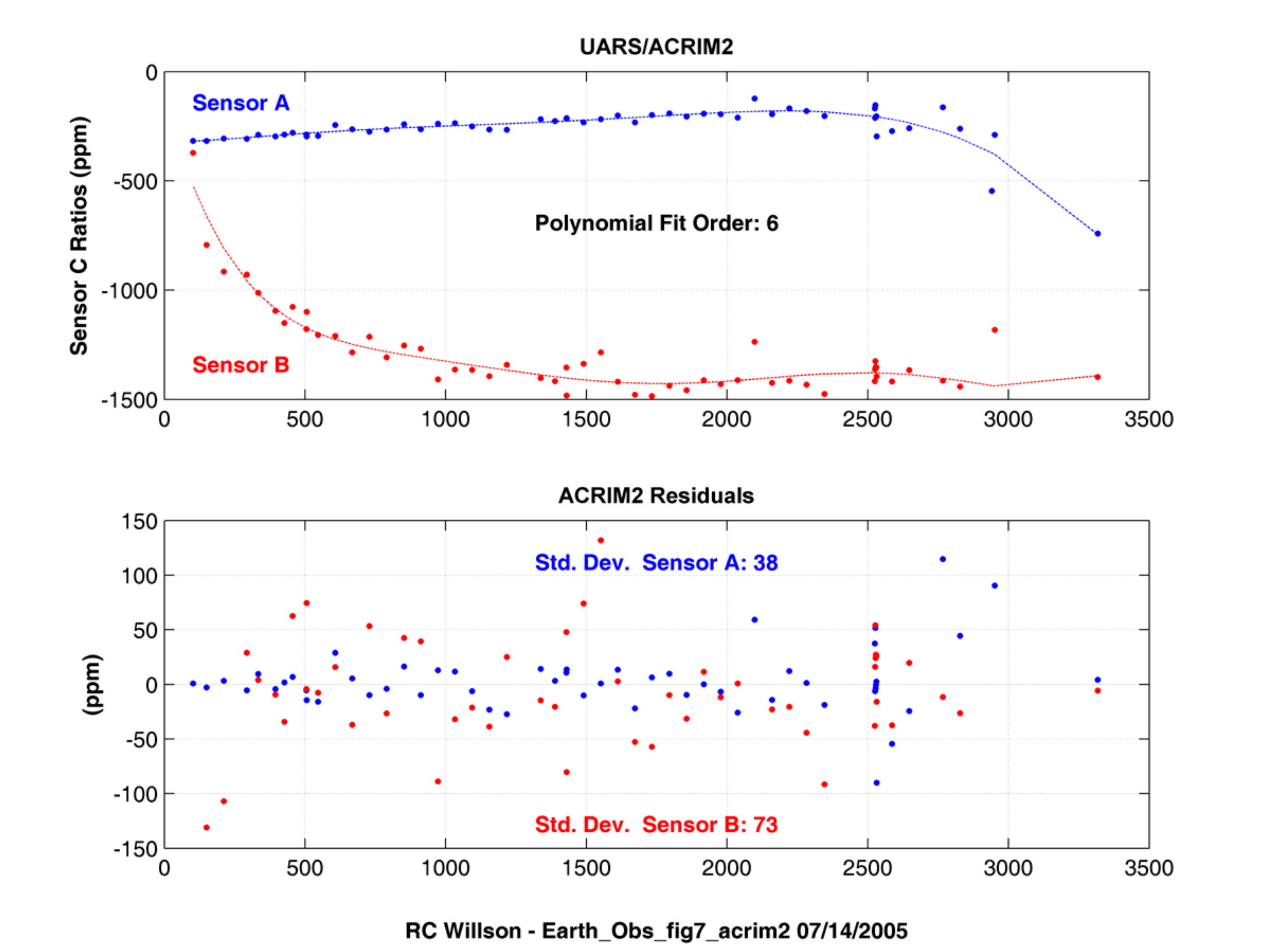


Sensor Experiment	C/A ratio	C/B ratio	A/B ratio	Range %
SMM/ACRIM1	0.999480	1.000501	1.001021	0.1021
UARS/ACRIM2	1.002187	0.998088	0.995910	0.4090
ACRIMSAT/ACRIM3	1.002068	1.001174	0.999108	0.2068

ACRIM1 Comparisons & Degradation Calibrations



ACRIM2 Comparisons and Degradation



ACRIM3 Comparisons and Degradation