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ABSTRACT

The Improved Stratospheric and Mesospheric Sounder (ISAMS) is an infrared spectroradiometer that formed part of the science instrument payload of the Upper Atmosphere Research Satellite. An essential part of the success of ISAMS in orbit was a program of prelaunch calibration and characterization of many aspects of the instrument’s performance. A brief description of ISAMS is followed by a detailed discussion of the calibration and characterization methodology, the facilities used in this program, and the results from the spectral and radiometric measurements. The results are discussed in terms of factors affecting the in-flight performance of ISAMS, particularly the spectral response of the measurement channels, the radiometric linearity, stray radiations and their dependence on the line of sight view, signal-to-noise ratios, and the sensitivity of the in-flight radiometric calibration to anticipated changes to the thermal environment within ISAMS. Some of the “lessons learned” are discussed with reference to the ISAMS design and the design of future instruments and test facilities.

1. Introduction

The Improved Stratospheric and Mesospheric Sounder (ISAMS) is a multichannel spectroradiometer that forms part of the scientific payload of the Upper Atmosphere Research Satellite (UARS), which was launched in September 1991 into a near-circular, 57° inclination, 585-km altitude earth orbit. UARS has several science objectives (Banks et al. 1978); the data from ISAMS contribute mainly to the understanding of the role of nitrogen oxides and aerosol particles in stratospheric ozone depletion, dynamical phenomena in the middle atmosphere, and the behavior of water vapor in the stratosphere.

This is the first of two papers describing the preflight calibration and characterization of ISAMS, carried out in 1989–90 at the calibration facility in the Atmospheric Physics Laboratory of the University of Oxford. ISAMS is described in detail elsewhere (Taylor et al. 1988; Barnett et al. 1992; Taylor et al. 1993); a briefer description is given here (section 2) to supply necessary background. The calibration methodology is set out in section 3, and the calibration facility is described in section 4. The results of the spectral and radiometric calibrations are given in sections 5 and 6. The second paper (Palmer et al. 1996, submitted to J. Atmos. Oceanic Technol., subsequently referred to as Part II), contains details of other calibrations (field of view, pointing, pressure modulator calibrations). A number of problems with the interpretation of calibration data are reported, and these are currently being investigated; these two papers describe the status of the calibration as applied to data products that are currently available for scientific investigations (see, for example, Rodgers et al. 1996; Dudiha and Livesey 1996).

2. Instrument description

ISAMS is a limb-viewing infrared filter radiometer that uses gas correlation spectroradiometry to retrieve atmospheric temperature and the mixing ratio of a num-
ber of minor constituents in the stratosphere and mesosphere. A schematic diagram of the optical arrangement in ISAMS is shown in Fig. 1. One of two alternative limb views [to the anti-sun (+Y) side, or the sun (−Y) side of the spacecraft] can be selected by rotating the plane flip mirror M3. The line of sight (LOS) is determined by the position of the scan mirror M1A/B that can be rotated about two orthogonal axes. Rotation about the elevation axis produces a limb scan, whereby the tangent point altitude is scanned from 0 to greater than 150 km, while rotation about the azimuth axis scans the LOS a few degrees either side of a line perpendicular to the UARS flight direction. (The latter is needed to ensure that the component of earth rotation velocity along the line of sight is cancelled by an equal and opposite component of the UARS velocity, in order to minimize the Doppler shift between emission lines in the atmosphere and absorption lines in the gas correlation cells.)

The in-flight radiometric calibration scheme uses two views in addition to the atmospheric views: a view of a reference blackbody, selected by an intermediate position of the flip mirror M3, and a view of cold space, obtained by extending the normal scan well above the atmosphere. The foreoptics include a rotating 12-toothed mirror chopper, which chops the LOS between the atmosphere and a fixed view of cold space at a frequency of 1 kHz.

Each of the eight detector packages contains a four-element linear array. The instantaneous field of view (FOV) at the tangent point is shown in Fig. 2. Each of the four detector arrays in the upper or A group have nominally collocated fields of view, and likewise each of the four detectors in the B group, as indicated in Fig. 2. The spectral intervals for the eight detectors are defined by dichroic beam splitters and interference filters as indicated in Figs. 1b,c. In six cases, the interference filters are deposited on a cooled lens (L5), which is the final optical element before the detector array, and in two cases they are deposited on plane-parallel elements mounted in two four-position filter wheels. Two filters in each filter wheel are designed to isolate regions of relatively strong and weak emission in the CO₂ 15-μm band for temperature sounding. The remaining filters are designed to isolate as far as possible emissions from

Fig. 1. Schematic diagram of the ISAMS optical arrangement: (a) foreoptics, (b) secondary optics, (c) pressure modulator and detector optics for one channel. The bandpass-defining filter is located on L5 as shown for channels 0–2 and 4–6, and for channels 3 and 7 on a filter wheel placed between L3 and F2.
Fig. 2. Schematic representation of the ISAMS IF0V at the tangent point; H1 = 2.6 km, H2 = 36 km, H3 = 10.4 km, W = 18 km.

Atmospheric HNO₃, O₃, aerosols, and N₂O₅. In addition to these filter-defined spectral bandpasses, each spectral channel contains a gas correlation pressure modulated cell (PMC); the gas contained in each cell is indicated in Fig. 1b. It can be seen that the filter wheels are located behind the CO₂ modulators; the other filter wheel channels, whose target gases cannot be contained in a PMC, are located in regions where CO₂ has no significant absorption. The technique of pressure modulation has been described in detail elsewhere (Taylor 1983). The PMC modulates radiation from the scene only at infrared frequencies for which the transmittance of the gas cell varies during the pressure cycle, whereas the rotating mirror chopper modulates all radiation within the spectral passband of a given channel. Since emission from a given gas in the atmosphere is highly correlated in frequency to absorption by the same gas in the PMC, whereas emission from other atmospheric gases within the same spectral passband is not, pressure modulation radiometry can give improved capability to retrieve the concentration of a given atmospheric gas compared with filter radiometry. The PMCs are described in more detail in Part II.

ISAMS returns signals derived from both the rotating mirror chopping (wideband or WB signals) and from the pressure modulation (pressure modulated or PM signals). The WB signal is independent of the gas correlation (except for the presence of a gas cell in the optical path), and is analogous to the output of a conventional filter radiometer, while the PM signal has the additional advantages of the gas correlation technique referred to above. The output signals from the detector arrays are processed with conventional analog preamplifiers and filters, followed by synchronous demodulation at the 1-kHz mirror chopping frequency to generate the WB signal and a second synchronous demodulation at the PMC frequency to generate the PM signal, followed in each case by digitizing integrators. The integration time for channels associated with each PMC is set to an integral number (NINT) of modulator cycles, and the number of 32-kHz clock cycles required (TINT) is simultaneously counted. One integration is carried out by each channel during one ISAMS measurement period (IMP; 1IMP = 2.048 s). The eight sets of NINT and TINT values, along with the 64 signal channel counts S, form part of the data transmitted each IMP; the ratio S/TINT is proportional to the measured radiance, while NINT/TINT is proportional to the PMC frequency. Radiometric calibration is discussed further in sections 3 and 6, and the use of the PMC frequency in calibration in Part II.

ISAMS has a total of 24 spectral channels: six detector arrays each giving PM and WB outputs, and two detector arrays each giving PM and WB outputs for two filter wheel positions, and WB only outputs for the other two filter wheel positions. These are identified by codes of the form \textit{n}mX, where \textit{n} is the PMC gas (0—CO, 1—H₂O, 2—N₂O, 3—CO₂, 4—NO, 5—NO₂, 6—CH₄, and 7—CO₂), X indicates the modulation source (P—pressure modulated, W—wideband modulated), and \textit{m} is zero except for the filter wheel channels, for which it identifies the filter. For the A group filter wheel, 30 indicates the strong CO₂ filter, 31 the weak CO₂ filter, 32 nitric acid, and 33 ozone. For the B group filter wheel, 70 and 71 are nominally identical to 30 and 31, 72 indicates the dinitrogen pentoxide filter, and 73 the aerosol filter. When it is necessary to identify an individual detector array element, they are numbered vertically in each group from 0 at the highest altitude to 3 at the lowest. These channel assignments are summarized in Table 1.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Target gas</th>
<th>50% points (cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0W</td>
<td>CO</td>
<td>2176–2257</td>
</tr>
<tr>
<td>10W</td>
<td>H₂O</td>
<td>1444–1515</td>
</tr>
<tr>
<td>20W</td>
<td>N₂O</td>
<td>1262–1298</td>
</tr>
<tr>
<td>30W</td>
<td>CO₂</td>
<td>628–655</td>
</tr>
<tr>
<td>31W</td>
<td>CO₂</td>
<td>605–624</td>
</tr>
<tr>
<td>32W</td>
<td>HNO₃</td>
<td>860–898</td>
</tr>
<tr>
<td>33W</td>
<td>O₃</td>
<td>990–1010</td>
</tr>
<tr>
<td>40W</td>
<td>NO</td>
<td>1856–1932</td>
</tr>
<tr>
<td>50W</td>
<td>NO₂</td>
<td>1595–1629</td>
</tr>
<tr>
<td>60W</td>
<td>CH₄</td>
<td>1320–1372</td>
</tr>
<tr>
<td>70W</td>
<td>CO₂</td>
<td>628–655</td>
</tr>
<tr>
<td>71W</td>
<td>CO₂</td>
<td>605–625</td>
</tr>
<tr>
<td>72W</td>
<td>N₂O</td>
<td>1224–1249</td>
</tr>
<tr>
<td>73W</td>
<td>Aerosol</td>
<td>818–833</td>
</tr>
</tbody>
</table>
The in-flight calibration blackbody (CBB) consists of a cone 70 mm deep with a half-angle of 28.5°, coated on the inside with Chemglaze Z306 Black Velvet paint. The wide end of the cone is covered by a flat plate with a central aperture measuring 10 mm × 12 mm, at the center of which the detector elements are imaged. The exterior surface of the CBB is gold coated to minimize radiative coupling to the instrument housing. The CBB is attached to the optics mounting plate (OMP) by means of three low-conductivity glass fiber legs. The CBB temperature is measured by a redundant pair of rhodium–iron resistance thermometers and a precision thermistor, which are embedded in the narrow end of the cone assembly, together with a pair of resistive heating elements and a single control sensor forming part of a thermostatic control loop.

Most of the optical components are bolted to the OMP, the temperature of which is controlled and adjustable within the range 288–293 K. However, the foreoptics mirrors shown in Fig. 1a have an equilibrium temperature cooler than this, around 278 K. As we shall see in section 6, for radiometric calibration reasons it is desirable that some of these mirrors are held at the same temperature as each other, so these components are also temperature-controlled, but at a lower temperature. The detector element packages are mechanically mounted on the OMP, but the detector arrays and the L5 lenses are mounted within them on low-conductivity supports, so that they can be cooled to their operating temperature of around 90 K, using a pair of long-life Stirling cycle coolers (Werrett et al. 1985; Bradshaw et al. 1985). ISAMS and the Along Track Scanning Radiometer (Deelderfield et al. 1985) are the first space instruments in which such coolers have been used.

The ISAMS Command and Data Handling System (CDHS) is based on a redundant pair of RCA CDP 1802 microprocessors, each with 16-kbyte CMOS RAM. The system design extends the 1802 microprocessor’s own data bus into a bidirectional instrument data bus on which all connected circuits are either listeners or talkers with unique addresses. The CDHS has two functions: to assemble data for transmission to the satellite once per IMP and to execute commands by sending data to listeners, such as mechanisms, demodulation phase shifters, and thermostats. A high-level control language, Programmed Control Language (PCL) with arithmetic operators, loop constructions etc., is provided to enable nonspecialists to write instrument command sequences. PCL code is compiled and assembled on an instrument support computer and the resulting file of microprocessor instructions transmitted to the instrument microprocessor for execution. The 1802 instruction set is not well matched to the task of writing these sequences, so an interpreter runs in the microprocessor, which uses a list of memory addresses to point to blocks of instructions that are then executed, possibly making use of data also in the list. A stack-based system is used in which all arithmetic and memory addressing is carried out via the stack. This is ideal for supporting arithmetic expression evaluation with parentheses, indexed addressing of data arrays and parameter passing to subroutines. The assembler, written in FORTRAN77, handles both native 1802 assembler commands and the pseudo (interpreted) commands. A memory load address has to be provided so that absolute addresses can be calculated. The compiler, also written in FORTRAN77, parses the input high-level language into segments (instruction, variable, operator, etc.) and generates 1802 assembler and interpreter instructions as output. The CDHS executive provides eight virtual processors, each of which can run a separate program. No single command or data item requires updating more frequently than once per IMP so all eight programs are executed sequentially within each 2.048-s period. By ensuring that each program returns control to the executive as soon as practicable and that all processors are serviced within an IMP, an effective multitasking facility is thus available.

The provision of PCL was crucial to the success of the mission, as it meant that very complicated instrument command sequences could be coded by the personnel responsible for generating the relevant operational requirements. This led to a devolved form of command management in which each area of instrument performance (e.g., scan pattern, thermal control, PMC control) was the responsibility of a separate member of the flight operations group, each of whom acquired experience in writing PCL during the preflight testing. The necessary oversight was provided by the requirement to run all code on the software instrument simulator before it was run on ISAMS. The detailed design of the CDHS and PCL are described by Werrett (1991).

3. Calibration methodology

a. Calibration of radiometers

If we assume that the radiometer signal chain is linear, then a single output count \( S \) (normalized by the integration time \( T_{\text{INT}} \)) is related to the radiance \( R \) at the entrance pupil by

\[
S = C + G \int F(n, \nu) R(n, \nu) d\Omega d\nu. \tag{1}
\]

(1)

In (1):

- \( C \) is the offset count, defined as the output count with zero radiance at the entrance pupil, which includes both an electronic offset \( C_{\text{el}} \), and the signal resulting from the radiometric offset \( \Delta R \), which is the difference in instrument emission between the two halves of the chopping cycle: \( C = C_{\text{el}} + G\Delta R \).

- \( R(n, \nu) \) is the spectral radiance at the entrance pupil of the radiometer (assumed uniform over the entrance
pupil), in the solid angle \(d\Omega\) around the direction of the unit vector \(\mathbf{n}\), and in the wavenumber interval \(d\tilde{\nu}\) around the wavenumber \(\tilde{\nu}\);

\(F\) is the optics transmission function, which defines the spatial and spectral averaging performed by the radiometer; and

\(G\) is the system gain, including the reflectances or transmittances of spectrally flat optical elements, electronics gain, and the efficiency of the optical chopping and synchronous demodulation.

Since \(F\) and \(G\) simply multiply each other, we can move constant factors (independent of \(\mathbf{n}\) and \(\tilde{\nu}\)) between \(F\) and \(G\), allowing us to define the normalization of \(F\). We choose to define the integral over \(F\) to be unity:

\[
\int F(\mathbf{n}, \tilde{\nu}) d\Omega d\tilde{\nu} = 1,
\]

which is consistent with the definition of \(F\) as an averaging function. We indicate a mean spectral radiance—that is, a spectral radiance averaged spatially and spectrally using the optics transmission function \(F\)—by an bar over the radiance symbol:

\[
\bar{R} = \int F(\mathbf{n}, \tilde{\nu}) \bar{R}(\mathbf{n}, \tilde{\nu}) d\Omega d\tilde{\nu}.
\]  

Equation (1) then simplifies to

\[
S = C + G\bar{R},
\]  

which makes explicit that the gain factor \(G\) also contains the étendue and spectral bandwidth factors for the radiometer.

It follows that it is necessary to determine \(F\) for each radiometer channel in order to interpret flight radiances, and this is one goal of the prelaunch characterization program. However, this is a very large measurement task, as there are 96 different channel functions to be determined, each of which, in addition to its explicit dependence on three variables (\(\tilde{\nu}\) and two components of \(\mathbf{n}\)), may depend in a nontrivial way on various instrument parameters. The most obvious example of this is that the LOS depends on the scan mirror position, but there may also be a change with, for example, instrument temperatures. To complete this task in a reasonable amount of time, it is necessary to make the approximation that the field of view and spectral bandpass contributions are independent, so that \(F\) factorizes

\[
F(\mathbf{n}, \tilde{\nu}) = F_{\text{FOV}}(\mathbf{n}) F_{\text{spec}}(\tilde{\nu}).
\]

These functions can then be measured independently by separate pieces of test equipment, to be described in section 4.

The in-flight radiometric calibration of the simple, linear radiometer with gain \(G\) and offset \(C\) described by (3) can be accomplished as follows. Provided that \(G\) and \(C\) vary only slowly with time, they can be determined by occasional measurements of two known radiances. These are a space view" zero" radiance \(\bar{R}_0\) (genuinely negligible in orbit, provided the space view altitude is sufficient, and furnished in the prelaunch calibration by a low radiance target) and a "full scale" radiance \(B(T_b)\) furnished by a view of a blackbody at temperature \(T_b\). If the corresponding counts are \(S_0\) and \(S_b\), then from (3) we have

\[
S_0 = C + G\bar{R}_0
\]

\[
S_b = C + GB(T_b).
\]

These allow \(C\) and \(G\) to be determined, so that (3) can be rewritten as

\[
\bar{R} - \bar{R}_0 = \frac{S - S_0}{S_b - S_0} \left[ B(T_b) - \bar{R}_0 \right],
\]

which allows the unknown radiance \(\bar{R}\) to be determined from the corresponding signal counts. It is convenient to express this radiance in terms of a mean Planck radiance at a fixed temperature \(T_0\), rather than the actual CBB temperature \(T_b\), which may vary somewhat:

\[
\bar{R} = \frac{\bar{R} - \bar{R}_0}{B(T_0)} = \frac{S - S_0}{S_b - S_0} \frac{B(T_b) - \bar{R}_0}{B(T_0)},
\]

where \(\bar{R}\) is a normalized radiance, and all calibrated radiances are expressed in this way, with \(T_0 = 290\) K. Equation (7) describes the essential features of the in-flight radiometric calibration of ISAMS, although there are complicating features to be described in section 6.

A second goal of the preflight characterization was the verification of this scheme, calibration of the blackbody radiance, and the evaluation of certain calibration dependences.

b. ISAMS calibration and characterization program

The scientific test, calibration, and characterization of the ISAMS flight model took place in two phases: the first between June and November 1989 after the assembly of ISAMS by the prime contractor British Aerospace and before its delivery to NASA for integration onto UARS, and the second between July and October 1990, prior to final delivery of ISAMS to NASA. The purpose was to ensure that the radiometer channels were sufficiently well characterized to enable the measured radiances to be interpreted in the retrieval process. This involved measurement of those characteristics that can reasonably be assumed to remain constant over the life of the instrument, and establishing the calibration from telemetry of those characteristics that may vary, either as a result of instrument operation or time variation. Measurements in the calibration facility were also used for engineering purposes, for example, in the final optical alignment, and for validating the instrument thermal model.

The measurements to be described in these papers are as follows:
• The measurement of the spectral response function $F_{\text{spec}}$ for at least one element per spectral channel (section 5).
• The measurement of the signal-to-noise ratio in all channels and elements (section 6).
• A detailed radiometric calibration (section 6).
• The measurement of the alignment of the fields of view and the adjustment of the detector packages as necessary to obtain the correct relative and absolute positions, and the correct focus position (Part II).
• The measurement of the FOV function $F_{\text{FOV}}$ for all channels and elements (Part II).
• The calibration of the angle transducers on the elevation and azimuth axes of the scan mirror (Part II).
• The calibration of the PMCs to enable the gas cell contents to be determined from telemetry, which is required for the correct evaluation of $F_{\text{spec}}$ for the PM channels (Part II).

It was also necessary to measure some of these parameters over the range of thermal conditions likely to be present within ISAMS during its life in orbit.

The accuracies required in the various calibrations were governed by a technical specification derived from the ISAMS scientific objectives. These can be summarized as the daily global measurement of temperature on pressure surfaces from 15 to 80 km with a vertical resolution of 3 km and accuracy of 1 K, and the constituent abundances with an accuracy of 10%.

In some calibrations, particularly the spatial measurements described in Part II, there were detailed derived specifications for the value and knowledge of the quantities measured, and these are referred to in the appropriate sections. In other cases it was clearly understood that the scientific return from the mission would increase with increasing calibration accuracy, and the measurements were strictly on a “best efforts” basis.

The extent of the program and the time available to execute it were such that it was necessary on several occasions to operate the calibration facility on a 24-hour-per-day, 7-day-per-week basis. This was done by two teams working alternate 12-h shifts with a change-over period. The teams included scientists and engineers familiar with the operation of ISAMS and the test equipment, and operated subject to the ground rule that the instrument was attended at all times when powered or under vacuum.

4. The calibration facility

a. Infrastructure and system design

The ISAMS calibration and characterization was conducted in a purpose-built calibration facility at Oxford University. This consisted of a class 10,000 clean room containing a thermal vacuum chamber large enough to accommodate ISAMS, thermal environment walls close to the instrument to give a good simulation of the space thermal viewfactors, and the major items of test equipment, the blackbodies and collimator-monochromator system, to be described below. The vacuum chamber is shown in Fig. 3, which illustrates the relative position of ISAMS and the test equipment, in this case the calibration blackbodies. Three of the four
chamber sections were removable to allow relatively easy access to components inside the chamber. Evacuation of the chamber was performed with an automatic sequencer that controlled a rotary pump with mechanical booster and a rotary-backed oil diffusion pump. The latter had a refrigerated baffle between its throat and the vacuum chamber, and enabled a pressure of less than $1 \times 10^{-3}$ hPa to be maintained in the tank. The tank was vented to atmospheric pressure with dry nitrogen.

The instrument, mounted as shown in the vacuum chamber, was connected to the remote interface unit (RIU) simulator, which emulated the function of the interface between the UARS spacecraft and the ISAMS CDHS. The RIU simulator was connected to a DEC PDP11/23 with 1-Mbyte memory and 70-Mbyte hard disk, which was used for all the user interface activities. Peripherals included a magnetic tape drive, four VT100-compatible terminals, two laser printers and a line printer.

Two extremely useful features of the system design were the use of the instrument microprocessor to command the test equipment and the use of the instrument data stream to record data from the test equipment. This was implemented by extending the ISAMS 1802 data bus out of the instrument, so that items of test equipment, and a multichannel chart recorder, could appear to the microprocessor as additional talkers and listeners. Spare slots in the instrument data frame were allocated to input from test equipment monitors, and spare command addresses were allocated to the control of test equipment. By including variable names for these external functions in the high-level language, the control and monitoring of the test equipment became fully integrated with the instrument CDHS. The use of the instrument microprocessor to control and monitor the test equipment was a major advantage, particularly in developing observation sequences involving synchronization of test equipment and instrument mechanism commands, since all event timing was controlled by the same clock, or where instrument actions depended upon environment parameters, since all the data were available to the same processor. Examples of such sequences are the mapping of the field of view and measuring radiometric response—two of the most time-consuming operations in the characterization of an infrared instrument. The vital step was the development of a high-level language facility for the 1802 microprocessor.

The PDP11/23 computer ran the RSX11M+ operating system, which allowed memory easily to be shared between processes. A number of processes ran asynchronously with different priorities in the time-sharing environment provided by RSX11M+. These included a control process from which other processes could be started and stopped; a command process that sent the necessary bit strings to the RIU simulator; a data process that copied all data from the RIU simulator into the shared memory for access by other processes, and where necessary, converted binary data into engineering units (temperatures in degrees, etc.); and processes to maintain a command log and archive all received data onto disk and tape. In addition to these basic functions, three additional processes provided important facilities:

- A limits process compared the latest received data with pretabulated maxima and minima and issued warnings if the limits were exceeded. The table used by the LIMITS program could be changed manually by the operator. In some circumstances, it would have been useful if the choice of table could have been automatically selected using an item in the data stream or if some conditional structure could have been added to the limits test. Also, no general provision was made for checking rates of change of data items, and this would have been useful.
- A data monitoring process displayed selected data items in real time on the VT100 screens according to table-driven item selection and format criteria. Several carefully designed screen layouts were available, but the construction and modification of the tables was made as easy as possible so that all users could quickly inspect data of their choice. All displays included a time code and data frame counter for identification. A laser printer could be switched to provide hard-copy snapshots of any display screen.
- A separate process controlled the compilation, memory management, assembly, loading, verification and starting of the PCL programs running in the instrument microprocessor. The compiler would take PCL code and generate assembler input and memory requirements. The process would then locate suitable free contiguous memory space for the program, assemble the code into a microprocessor load file, and transmit it to the instrument microprocessor. A command to dump the appropriate section of memory followed the microprocessor load and the process then captured the output from the dump and verified that the load file had been correctly and fully transmitted. Having ensured that it was safe to do so, the process finally issued the command to start the program.

b. Radiometric test equipment

Two large full-aperture blackbody targets were used for the radiometric calibrations. They were located at the far end of the vacuum chamber from ISAMS, as shown in Fig. 3. One of these targets, the space-view blackbody (SBB) operated at liquid nitrogen temperature to provide the low radiance reference view $R_0$, which is the analog of the space-view in flight, while the earth-view blackbody (EBB) operated at a variable temperature between 80 and 300 K to provide known radiances $R$ between these limits. The construction of these targets has been described by Nightingale and Crawford (1991) and
Nightingale (1992). They consist of a vee-grooved baseplate 300-mm diameter and a tapering shroud with entrance aperture 200-mm diameter, all coated with 3M Nextel paint. The emissivity is estimated to be in excess of 0.99975 for all channels, and the two targets have matched emissivity to within $2 \times 10^{-5}$, which means that the effect of thermal radiation incident upon the targets and reflected into the ISAMS beam is cancelled to first order in the difference $R - R_0$. The thermometry was calibrated against United Kingdom secondary standards before and after the calibration program, and is estimated to be accurate to 60 mK.

A third radiometric target was provided for the chopper reference “space” view, which consisted of a grooved plate of similar design to the EBB and SBB baseplates, but without any shroud, and operated at liquid nitrogen temperatures. The quality of this blackbody was not important provided the radiance viewed by the instrument was stable, because all calibration measurements involved differences of signal counts, in which the size of this radiance cancels.

c. The collimator–monochromator system

The collimator–monochromator system (CMS) is shown in Fig. 4. The CMS could, when required, be mounted in the vacuum chamber between ISAMS and the blackbody targets, in place of the shroud shown in Fig. 3. The collimator consisted of a small infrared source (a globar behind an aperture) located at the focus of an off-axis paraboloid mirror approximately 250 mm in diameter, mounted in an open frame structure. This was carried on a two-axis gimbal driven by stepper motors through a reduction gear. Angular displacements of the gimbal were measured by linear capacitance transducers (LCTs). A black shutter between the globar and the pinhole was used to chop the globar radiation at a variable rate of 1 cycle per $n$ IMPs, where $n \geq 1$. The source assembly could be remotely moved along the principal axis of the optical system to deliberately defocus the collimator during adjustment of the ISAMS detectors for best focus position (see Part II).

The monochromator was mounted on the same structure as the collimator frame. A plane remotely controlled flip mirror was used to position the image of the monochromator exit slit at the focus of the off-axis paraboloid, thus imaging the slit onto the ISAMS detectors, with the long axis of the slit parallel with that of the detectors to within 2 arc min. The monochromator was a Ebert–Fastie grating spectrometer with 400-mm focal length and nominal focal ratio of 5.8 fitted with remotely adjustable curved entrance and exit slits. The radiation source was a second globar with a black shutter for source chopping at a $1/n$ IMP rate. The source temperature was monitored with a type K thermocouple mounted with ceramic putty at the back of the globar. A filter wheel carried four order-sorting filters that allowed virtually the whole ISAMS spectral range from 600 to 3000 cm$^{-1}$ to be used with a single 50-line-per-millimeter grating in three orders. The slits, grating, and filter wheel were driven by stepper motors, and their positions monitored with LCTs and Hall effect sensors.

The spectral variation of the monochromator output was measured separately with a spectrally flat bolometer detector [Mullard (UK) RPY91C1]. Because $F_{\text{spec}}$ is a normalized function, the applicable systematic error in the ordinate is a relative error across the band, and this is limited by the source stability. Over a number of hours, variations of $\pm 10$ K were observed in the globar thermocouple telemetry, probably due to slow drifts in the globar power supply. For the shortest wavelength ISAMS channel (channel 00, 4.51 $\mu$m), a 10-K change causes only a 0.4% change in the ratio of the Planck functions across the band. The error in the abscissa is given by the wavelength calibration, which was established by observing multiple high diffraction orders of a 0.5-mW HeNe laser, with an estimated accuracy of better than 0.5 cm$^{-1}$. More detail on the construction and calibration of the CMS is given by Morris (1992).

5. Spectral calibration

a. Measurements

Two types of spectral calibration scans were made, consisting of in-band spectral scans at 2-cm$^{-1}$ resolution, limited to just the main filter response, and out-of-band spectral scans at 5-cm$^{-1}$ resolution, that provided near-continuous coverage in the filter stop bands (Morris 1992). These out-of-band scans were designed to detect any significant filter “leaks” and in the shorter wave-
length channels provided measurements down to relative transmission levels of approximately 0.01%, but the measurements are noise-limited at higher levels than this in the longer wavelength channels.

The bolometric measurements of the monochromator output used the same slit widths as those selected for the instrument spectral calibration and the same globar temperature of 1270 K. The ISAMS spectral response function $F_{\text{spec}}(\tilde{\nu})$ can be expressed as

$$F_{\text{spec}}(\tilde{\nu}) = A \frac{S(\tilde{\nu})}{S_{\text{ref}}(\tilde{\nu})},$$

where $S(\tilde{\nu})$ and $S_{\text{ref}}(\tilde{\nu})$ are the signal counts as a function of monochromator wavenumber recorded by ISAMS and the reference detector (each a difference of values, shutter open minus shutter closed) and $A$ is a normalizing factor. Although $F_{\text{spec}}$ was defined above to be normalized to unity on integration, the response functions shown in the plots have been normalized to unity at the peak.

For the in-band scans, the exit slit of the monochromator was imaged on to the detector element closest to the ISAMS optical axis (element 3 for the A group channels and element 0 for the B group channels), as time constraints precluded measurements for all four elements, and because the inner elements were expected to be the least sensitive to ISAMS telescope aberrations. The spectral response functions for all the wideband channels are shown in Fig. 5.

The functions $F_{\text{spec}}$ are used to calculate tables of mean Planck radiances for radiometric calibration, as in (7), and tables of transmissions through uniform gas paths, used by the forward model in the retrieval process (Marks and Rodgers 1993; Dudhia and Livesey 1996). Several corrections to the directly measured WB functions defined in (8) have been made to give the functions shown in Fig. 5. The most important of these is for the effect of the PMC. In the wideband channels this effect is simply that of the gas cell in the optical path, which is included in these measurements, but only at very low resolution compared with the width of the gas absorption lines. For known cell conditions, the small gaseous absorption can be accurately calculated, so the effect of the gas in the PMC was divided out from the measurements at low resolution, to derive the transmission of the instrument with the PMC empty. The effect of the gas is then computed at very high resolution in the process of calculating the tables. For the PM channels a model of the gas pressure–temperature cycle and the effect of the signal processing electronics is used to calculate the spectral selection by the PMC, and this function is multiplied by the "empty PMC" transmission derived from the WB measurements. Thus, the PM measurements are not directly used at all, because the significant information in the PM channel $F_{\text{spec}}$ is at a much higher resolution than the measurements. However, the measured PM response functions have sufficient resolution to show clear evidence of the spectral selection of the modulator, with individual spectral lines being observable where the spectra are not too dense, and significant spectral features in the other cases. These measurements thus provided a cross check on the spectral calibration of the monochromator, which was accurate to better than 0.5 cm\(^{-1}\). Some of these are shown in Fig. 6.

Two other corrections have been applied to $F_{\text{spec}}$. In some cases, mostly due to time constraints when taking measurements, the high-resolution scans did not extend as far as necessary into the blocking regions, and the function was extrapolated to lower values. The out-of-band blocking measurements give us confidence that the function does continue to fall in this region, with the exception of the high frequency edge of channel 60, where a spectral leak was detected. The second correction was the removal of a ripple resulting from etalon fringes in an order-sorting filter in the monochromator.

![Fig. 5. Spectral response for ISAMS wideband spectral channels, showing the channel designation and the target gas. Channels 70W and 71W are excluded, as they have almost identical response to 30W and 31W.](image-url)
For the out-of-band measurements, the throughput was increased by degrading the monochromator resolution to 5 cm\(^{-1}\). The measurements were performed on element 1 for the A group detectors, and element 2 for the B group detectors. The spectral coverage extended down to approximately 4 \(\mu\)m, leaving an unsampled 2-\(\mu\)m gap before the intrinsic cutoff of the germanium optics at approximately 1.8 \(\mu\)m. Other unavoidable gaps were present between the order-sorting filter transmitting regions and at wavelengths longer than 17 \(\mu\)m, beyond which the bolometric output measurements were limited by poor signal-to-noise characteristics. This led to an incomplete coverage of the midinfrared spectral region, although it represented the best attainable from a single grating. Due to these gaps and time constraints, it was not always possible to measure both the short- and long-wavelength filter stopbands. Figure 7 indicates the extent of the out-of-band response in channels 10W and 60W. Only spectral intervals in the vicinity of the in-band responses are shown, beyond which the response fell below the measurement limit. Included in the figures are the theoretical bandpass filter transmissions supplied by the University of Reading (R. Hunneman 1989, personal communication), which provide an indication of the expected out-of-band transmission, excluding the spectral response of the low-pass blocking, beamsplitters, and detector. In most cases the measured blocking transmission agrees well with the theoretical results, even though the shape of the in-band responses differ significantly, as a result of the large cone-angle effects on the filter profile. The spectral leak observed in channel 60 appears to be a scratch imperfection affecting the low-pass blocking filter, as it is not seen in flight spare filters, and the leak extends with little spectral structure until it is cut off by a beam splitter.

b. Problems with spectral calibration

A number of problems with the spectral calibration data have emerged during detailed analysis.
Over the course of the two calibration campaigns, some channels, notably channel 00, were measured on several occasions, and there are systematic discrepancies between the repeated measurements. These take the form of apparent spectral shifts of the filter profile between measurements, of order 5 cm$^{-1}$. In addition, the out-of-band measurements were performed on a different element from the in-band scans, and these also show apparent shifts relative to the in-band scans in some cases. It is extremely fortunate that the PM spectral functions exhibit identifiable spectral features, which enable us to rule out errors in the wavelength calibration as the source of these discrepancies. The channels in which these effects are observed are the nonfilter wheel channels, and in these cases the filter is deposited on the L5 lens in front of the detector (Fig. 1c). The beam at this point has a very large cone angle, and so the filter measurement is very sensitive to the uniformity of the test beam. We have recently discovered that one of the optical elements in the monochromator was undersized, so that the test beam was, at best, marginal in size and uniformity. It is thus possible that differences in alignment between the CMS and ISAMS could lead to the shifts observed. However, the large cone angle through the filters in these channels also leads to sensitivity to the very small changes in the radiometer beam that occur between different elements of the detector array. It is thus possible that some of the inter-element shifts represent real spectral differences, resulting from the different spatial and angular illumination of the filters for different elements. Measurements on the filter wheel channels did not exhibit these problems and were very reproducible. The radiometric calibration also produced indirect evidence for spectral shifts, so this problem will be discussed further in section 6.
6. Radiometric calibration

a. Measurements

Radiometric calibration measurements were made with the CMS removed from the thermal vacuum chamber, and replaced by a liquid-nitrogen-cooled black baffle enclosing the view to the two large calibration blackbodies, the EBB and SBB. The scan and flip mirrors were driven through a programmed sequence of views of these targets, and views of the CBB, while the EBB output was varied over the whole range of expected radiances. The EBB radiance deduced from the instrument, using the SBB and CBB views as the calibration views, can then be compared with the radiance calculated using the measured spectral profile and the EBB temperature. Two different types of EBB variation were used: temperature ramps and plateaux. In the ramp mode, the EBB was heated or cooled continuously between liquid nitrogen temperatures and about 300 K; this mode was used for noise measurement, as the output radiance could be assumed to vary smoothly over any short interval. However, even for ramps taking 12 h, the heating rate was sufficient to introduce a significant difference between the measured temperature and the effective radiating temperature, so for the linearity calibration the EBB was heated or cooled to a number of set-points, or plateaux, and measurements made in thermal steady-state conditions. These runs typically took 30 h.

Data from the signal channels were collected in a cycle consisting of groups of 32 IMPs viewing the EBB and 16 IMPs viewing each of the SBB and CBB, with each of these blocks of data subdivided by filter wheel rotations for channels 3 and 7. Both ramp and plateau data were analyzed in the same way: a low-order polynomial was fitted through each group of signal channel counts, from which a single representative value was calculated at its midpoint, along with the standard deviation for the fit that was taken as an estimate of the noise associated with a single sample.

Owing to its complexity and the low noise of its wideband channels, the radiometric calibration of ISAMS presents a considerable challenge. The large number of individual channels (96) that require characterization is a data processing problem, but unlike the spectral calibration, where time constraints prevented measurements on every element, we can collect data for most of the channels simultaneously, although in the case of the filter wheel channels only a quarter of the time used for the other channels is available. However, the noise performance means that a high accuracy is required to realize the full potential of the instrument. Indeed, it is quite unrealistic to expect to be able to calibrate down to the noise level at all input radiances in some of the channels, but since the calibration method discussed in section 3, and in more detail below, relies explicitly on linearity, it is necessary to demonstrate this over as wide a range of input radiances as possible. It is therefore only to be expected that we shall observe systematic effects above the noise level, but hopefully below the level at which they are significant operationally, and indeed a number of subtle anomalies have come to light in the course of the radiometric calibration. In particular, the various channels show radiometric offsets that depend upon the position of the scan mirror. There is also some circumstantial radiometric evidence, referred to in section 5, for an apparent shift in some filter passbands between the spectral and radiometric calibrations, and for differences in filter passbands between the elements of some channels.

A radiometric mathematical model of the instrument is required to interpret calibration data. This is developed below and then used to retrieve calibration coefficients. A single channel, 20W, has been used to demonstrate the various aspects of the instrument’s radiometric performance where possible.

b. ISAMS radiometric models

The ISAMS in-flight calibration scheme is not the ideal one described in section 3, as the high-radiance gain measurements $S_b$ of the CBB are not made through the same optical train as the atmospheric and low-radiance offset measurements $S$ and $S_0$. As a result, ISAMS is sensitive to foreoptics emissions. The radiance incident on the flip mirror M3 (see Fig. 1a) when observing the CBB is

$$\widetilde{R}_3 = \{ \tilde{B}_{\mu} \xi_{\mu} + \tilde{R}_s \} (1 - \epsilon_s) (1 - \epsilon_t) + \tilde{B}_{\epsilon} \xi_{\epsilon},$$

(9)

where $\tilde{B}_{\mu}$ and $\tilde{B}_{\epsilon}$ are the mean Planck radiances due to the CBB and the ellipsoid folding mirror M7 [the former having been referred to as $B(T_b)$ in section 3]; $\tilde{R}_s$ is the radiation in the CBB environment reflected or scattered into the beam; and $\epsilon_s$ and $\epsilon_t$ are the emissivities of the CBB and M7. The radiance at the flip mirror when observing the atmosphere is

$$\widetilde{R}_3 = [\widetilde{R}(1 - \epsilon_1) + \tilde{B}_1 \xi_1] (1 - \epsilon_2) + \tilde{B}_2 \xi_2,$$

(10)

where $\widetilde{R}$ is the atmospheric radiance; $\tilde{B}_1$ and $\tilde{B}_2$ are the Planck radiances due to the plane scan mirror M1A/B and the primary paraboloid M2A/B, and $\epsilon_1$ and $\epsilon_2$ are the mirror emissivities. The radiance for the space view is identical in form to (10):

$$\widetilde{R}_3 = [\widetilde{R}_0 (1 - \epsilon_1) + \tilde{B}_1 \xi_1] (1 - \epsilon_2) + \tilde{B}_2 \xi_2,$$

(11)

where for orbital observations, $\widetilde{R}_0$ is a view to cold space and can be neglected, while for laboratory observations the "space view" to the SBB generates detectable radiances in the longest wavelength channels $[\sim 2 \times 10^{-4} \tilde{B}(T_0)].$

Provided that the instrument responds linearly to an observed radiance, generating counts $S$, $S_0$, and $S_b$ according to (3), the ratio of differences $(S - S_0)(S_b - S_0)^{-1}$ can be written explicitly as a ratio of the radiances from the CBB, limb, space, and the foreoptics mirrors by combining (9), (10), and (11):
\[
\frac{S - S_0}{S_b - S_0} = \frac{(\bar{R} - \bar{R}_0)(1 - \epsilon_1)(1 - \epsilon_2)}{\bar{B}_b(1 - \epsilon_b)(1 - \epsilon_1) + \bar{B}_e\epsilon_7 - \bar{R}_0(1 - \epsilon_1) + \bar{B}_e\epsilon_7 - \bar{B}_2\epsilon_2}.
\]

This can be written
\[
\bar{R} - \bar{R}_0 = \frac{S - S_0}{S_b - S_0} (\bar{B}_b - \bar{R}_0),
\]
where
\[
\bar{B}_b = \bar{B}_b + (\bar{R}_b - \bar{B}_b) \left( \frac{1 - \epsilon_b}{1 - \epsilon_1} \right) (1 - \epsilon_2) + \frac{\epsilon_7}{(1 - \epsilon_1)(1 - \epsilon_2)}
\]
\[- (\bar{B}_2 - \bar{B}_b) \frac{\epsilon_2}{(1 - \epsilon_1)(1 - \epsilon_2)} - (\bar{B}_1 - \bar{B}_b) \frac{\epsilon_1}{(1 - \epsilon_1}).
\]

Comparing (12) with (6) we see that \( \bar{B}_b \) is the equivalent radiance for a "virtual" blackbody at the aperture of the instrument. It can be seen from (13) that \( \bar{B}_b \) differs from \( \bar{B}_0 \) only due to differences between the temperature of the CBB and those of the CBB environment and the foreoptics mirrors. For this reason, the foreoptics temperatures are kept near to that of the CBB so that the calibration process is insensitive to errors in the values of the mirror emissivities. Furthermore, the coefficients of these terms are all small, because the CBB has very low reflectivity: \( 1 - \epsilon_b \approx 4 \times 10^{-4} \), and the mirrors have low emissivity: \( \epsilon_1, \epsilon_2, \epsilon_7 \approx 0.01 \). Values for the mirror emissivities \( \epsilon_1, \epsilon_2, \text{ and } \epsilon_7 \) can be extracted by regressing the ISAMS radiometric model on to the telemetry from a special prelaunch calibration sequence, in which each foreoptics mirror temperature was elevated in turn by approximately 5 K while a repeated background cycle of SBB, EBB, and CBB radiance measurements was taken (see Fig. 8). The form of (12), with \( \bar{B}_b \) as in (13), is used in the operational radiometric calibration. However, the term involving \( \bar{R}_0 \) cannot be calculated operationally, as many surfaces at different temperatures can radiate into the CBB. This term is thus a source of gain error of about 0.02%, based on the above value of \( 1 - \epsilon_b \) and the assumption that \( |(\bar{R}_0 - \bar{B}_b)| \ll 0.5\bar{B}_b \).

Straightforward use of (12) to calibrate radiances observed in the vacuum chamber indicated significant offset problems: at low EBB temperatures, as \( \bar{R} \rightarrow 0 \) the calibrated value of \( \bar{R} \) did not tend to zero, but to an offset value on the order of 0.01 \( \bar{B}(T_0) \) in some channels. Similarly, signals calibrated with (12) after launch indicated detected radiances well into the expected space-view altitudes. The only instrumental change between a high atmospheric observation \( \bar{R} \) and a space view \( \bar{R}_0 \) is the movement of the scan mirror, and the corresponding movement of the scanned beam as it passes through the instrument outer structure. If this generates a change in output count for no change in input radiance, there must be some change in the

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Fig. 8. Top panel: Mirror temperatures during the mirror emissivity calibration sequence. Middle panel: Fractional difference between calculated input radiance and ISAMS measured radiance in channel 20W element 3, calibrated with Eqs. (12) and (13), with mirror emissivities set to zero. Lower panel: As middle panel but with best fit mirror emissivities.
radiometric offset $\Delta R$ between these views. This effect is referred to as a scan-dependent stray radiance, or scan stray.

Various physical mechanisms can lead to scan strays. Direct obstruction of the scanned beam by the instrument structure is unlikely, as the alignment of the telescope optics was verified with visible light. However, the final alignment of each channel, involving the placement of all pupils and field images, was done in the infrared, as described in Part II, so some marginal interference of the scanned beam is possible. More plausible mechanisms involve consideration of the reflection and emission processes at the scan mirror surface, represented in (11) by the term $\bar{R}_0(1 - \epsilon_1) + \bar{B}_1\epsilon_1$. The changing beam shape on the mirror surface as it rotates, coupled with thermal nonuniformity, could make the effective value of $\bar{B}_1$ scan-dependent, while angle-dependence or spatial nonuniformity of $\epsilon_1$ could make the effective value of the emissivity scan-dependent. Alternatively, the assumption that the specular reflectivity is $(1 - \text{emissivity})$ could be invalid because of a significant degree of nonspecular reflection, due to, for example, contamination of the mirror surface. These last two mechanisms also lead to a scan-dependent gain variation through the effect on the scan mirror specular reflectivity, which is one factor in the overall instrument gain.

We can analyze the effect of scan stray by returning to the three-view calibration equations introduced in section 3, (3), (4), and (5), but making the gains and offsets scan-dependent. We define the gain when the elevation scan angle is $\theta$ to be $G(\theta)$ and the offset count to be $C(\theta)$. (We are here ignoring the azimuth dependence of these quantities for simplicity.) The space view scan angle is denoted $\theta_0$.

$$S = C(\theta) + G(\theta)\bar{R}$$  \hspace{1cm} (14)

$$S_0 = C(\theta_0) + G(\theta_0)\bar{R}_0$$  \hspace{1cm} (15)

$$S_b = C(\theta_0) + G(\theta_0)\bar{B}_b.$$  \hspace{1cm} (16)

Equations (14) and (15) define the output counts in the atmospheric and space views in terms of the input radiances and instrument gains and offsets. In (16) we have retained the concept of the virtual blackbody $\bar{B}_b$ at the entrance aperture giving the same output count as the actual view to the CBB, but it is now necessary to specify the viewing direction, which we choose to be the space view. Thus, (16) is in effect a definition of $\bar{B}_b$ in terms of the space view gain and offset. The explicit form of $\bar{B}_b$ will be similar to (13), but depending on the scan stray mechanism, there will be changes in detail. Similarly, there may be necessary connections between the differences $C(\theta) - C(\theta_0)$ and $G(\theta) - G(\theta_0)$, but these are also model-dependent. We cannot now eliminate all the unknown gains and offsets, but from (14)–(16) we can derive

$$\bar{R}' - \bar{R}_0 = \frac{(S - S_0) - [C(\theta) - C(\theta_0)]}{S_b - S_0} (\bar{B}_b - \bar{R}_0),$$  \hspace{1cm} (17)

where $\bar{R}' = [G(\theta)/G(\theta_0)]\bar{R}$. Thus, if the scan stray effects cannot be estimated then comparison of (17) with (12) shows that they introduce scan-dependent offset errors due to $C(\theta) - C(\theta_0)$, and scan-dependent gain errors, involving both $G(\theta)/G(\theta_0)$ and any additional terms in $\bar{B}_b$ that we are unable to model correctly. The effect on the preflight calibration data will therefore be a fixed offset and gain error in each channel because the EBB and SBB are observed at different but fixed scan mirror positions. In orbit we can simplify (17) by setting $\bar{R}_0$ to zero. We also collect all the gain effects into a scan-dependent virtual blackbody $\bar{B}_b(\theta) = [G(\theta)/G(\theta_0)]\bar{B}_b$, and define a scan-dependent virtual space view $S_b(\theta) = S_0 + [C(\theta) - C(\theta_0)]$. (In this context the latter may seem a circuitous definition, since $S_0(\theta) = C(\theta)$, but $C(\theta)$ is not available to us, whereas $S_0$ is an actual space view count, and $C(\theta) - C(\theta_0)$ is the scan stray offset, the measurement of which is discussed below.) With these substitutions, (17) becomes

$$\bar{R} = \frac{S - S_0(\theta)}{S_b - S_0(\theta_0)} \bar{B}_b(\theta).$$  \hspace{1cm} (18)

c. Treatment of scan stray

Direct measurement of the scan stray offset is possible in flight by using cold space as a large low-radiance target. For three hours, starting late on 30 September 1990, twenty days after launch, the complete $U$ARS satellite executed a roll maneuver, rotating by 10° about its line of flight so that the scan ranges of the $+Y$ viewing instruments were lifted above the atmospheric limb. In this orientation, ISAMS made repeated interleaved "raster" scans of cold space. At the end of each elevation cycle, the azimuth position was incremented and calibration measurements of the CBB and "high space" were made. Corresponding measurements on the $-Y$ side were attempted later in the mission, but are more difficult as the chopper reference view on the $+Y$ side of the instrument descends into the top of the atmosphere as the satellite is rolled in this direction. There is no direct way of measuring any gain error resulting from scan stray in flight. Thus, in terms of the quantities introduced above we can estimate $C(\theta) - C(\theta_0)$, and hence $S_0(\theta)$, but not the $\theta$ dependence of $\bar{B}_b(\theta)$.

The offset in counts can be calculated straightforwardly from (18), setting $\bar{R}$ to zero:

$$C(\theta) - C(\theta_0) = S - S_0.$$  \hspace{1cm} (19)

This count can be calibrated to give an offset radiance in the usual way, subject to the same gain uncertainties noted above as any other radiance. In practice, much
larger errors are likely to arise from the assumption that
the scan stray measured during the rollup is the same
as the scan stray during limb observations, as the ther-
al environment will have changed slightly, and at
least some of the scan stray is likely to be due to scat-
tered earthshine rather than direct instrument emis-
sion.
The measured scan stray offsets are very puzzling.
In almost all the nonfilter wheel channels, the offset
varies by a few times the wideband noise level over the
atmospheric scan range (0–150 km), diminishing with
height in the +Y view. The radiance difference over
this range is about 2–10 × 10^{-5} \tilde{B}(T_0). The exceptions
are elements 0 and 1 of channel 10 where the offset
decreases with height; for element 1 it is comparable
in size with the other elements, while for element 0 it
is about six times larger. In channels 3 and 7 there
is good consistency between the offset measured with dif-
ferent filters and the same detectors, but very little
agreement between the filter wheel offsets and the col-
located nonfilter wheel offsets in each group: in chan-
nel 3 the offsets decrease with height, show a marked
element dependence unlike the other A group channels,
and are much larger, 60–50 × 10^{-5} \tilde{B}(T_0), while in
channel 7 the offsets vary in the same sense with height
as the other B group channels, but are much larger,
50–80 × 10^{-5} \tilde{B}(T_0) for elements 0–2, and about 350
× 10^{-5} \tilde{B}(T_0) for element 3. This probably implies
that there are two mechanisms generating the stray: the
small and fairly consistent strays in the nonfilter wheel
channels are of a size such that any of the normal scan
stray mechanisms listed above could be responsible,
while the larger strays in some elements of channels 1,
3, and 7 seem more likely to result from some marginal
misalignment.

At present, two approaches to this problem have
been taken, one for the analysis of prelaunch calibration
data and another for operational radiometric calibra-
tion. For operational purposes, the scan stray is only
significant at the highest altitudes giving detectable ra-
diances, as the presence of the scan stray offset leads
to an observed radiance profile that does not go to zero
at these altitudes, and the gain error is expected to be
unimportant at these low radiance levels. The current
scheme is based on using the measured scan stray offset
(19) in (18). While this improves the high-altitude ra-
diances, it does not entirely cure the problem, as the
size of the scan stray is found to vary over the course
of the mission. The simple subtraction has therefore
been replaced by a more complicated scheme, whereby
the derivative of the scan stray with respect to elevation
angle is determined from high-altitude radiance mea-
surements that are expected to be zero, and divided by
the corresponding slope of the directly measured scan
stray to calculate a scaling factor. The measured scan
stray is then scaled by this factor before subtraction.
Scaling factors are calculated daily, and show variation
on all longer timescales. The underlying assumption
here is that the shape of the measured scan stray offset
is constant, and only its magnitude varies; in the ab-
ance of frequent direct measurements of the offset, the
only test of this assumption is the use of the operational
algorithm to calibrate radiances measured during a sec-
ond rollup maneuver later in the mission. The opera-
tional radiometric calibration is described in more de-
tail by Rodgers et al. (1996).
The approach taken for the analysis of the prelaunch
calibration data has been to select a particular radiom-
etric model of the scan stray and to use the postlaunch
rollup data and the prelaunch calibration data to deter-
mine its coefficients. This leads to specific, though
model-dependent, connections between \( G(\theta) - G(\theta_0) \)
and \( C(\theta) - C(\theta_0) \), and to an additional term in \( \tilde{B} \).
This extended radiometric model is then used to inter-
pret the linearity data. Full details are given by Night-
gale 1992. The advantage of this approach is that gain
corrections can be treated in a consistent way. The dis-
advantages are that the results may be slightly model-
dependent, and the assumption that the postlaunch scan
stray measurements can be applied to the prelaunch
data is likely to lead to an incomplete removal of scan
stray.

It is clear from the above that the scan stray removal
and the extraction of mirror emissivities are interde-
dependent, as the regression to extract the mirror emis-
sivities \( \varepsilon_1 \), \( \varepsilon_2 \), and \( \varepsilon_3 \) requires scan stray removal, and
the calibration of the scan stray requires \( \tilde{B} \), which de-
pends on the emissivities and the scan stray model pa-
rameters. In practice, an iterative approach was adopted
to obtain a self-consistent set of parameters.

d. Linearity

Linearity data were generated by stepping the tem-
perature of the EBB either up or down between
twenty constant temperature plateaux, spaced at in-
tervals of approximately 0.05 \( \tilde{B}(T_0) \) in the 16.3-\mu-
channels (31P, 31W, 71P, and 71W). Data were
therefore biased toward low radiance values in the
shorter wavelength channels, but this generally re-
lected the distributions of atmospheric radiances in
these channels. Calibration values were calculated
only for signal channel data taken at these plateaux.
Figures 9 and 10 show the residual radiances that
remain after the calculated EBB radiance has been
subtracted from the calibrated signal channel radi-
dances in channels 20W and 20P, and 71W and 71P.
These represent, respectively, the most extreme de-
viations in nonlinearity and offset. As mentioned
above, the omission of scan stray in this comparison
leads to comparatively large radiance offsets at low
EBB radiance, particularly in the outer elements (el-
ment 0 of A group channels, and element 3 of B
group channels). The inclusion of scan stray reduces
these offset radiances by factors of between 4 and
10, and the gain errors are also reduced, to give the
results shown in Figs. 9 and 10. Nonlinearities in channels 00W, 10W, and 20W were clearly apparent. Small nonlinearities could also be seen in channels 40W, 50W, and 60W. Corresponding nonlinearities were sometimes discernable in the corresponding PM channels, where they were not obscured by noise.
Gross errors in the thermometer calibrations could be ruled out as the source of the nonlinearities, as deviations of the same sign and with predictable amplitudes would be expected in all spectral channels. This was not the case. In addition, nonlinearities due to the detectors were considered unlikely as the ob-
served nonlinearities are present only in channels with photovoltaic detectors, which are intrinsically linear devices over a large dynamic range, and not in the filter wheel channels, which used photoconductive detectors and might be expected to show small linearity errors. [This effect arises because the voltage responsivity for photoconductive HgCdTe is proportional to the effective carrier lifetime (Broudy and Mazurczyk 1981), and the Auger contribution to the recombination rate increases with carrier density (Peterson 1981).]

A further candidate mechanism was a difference between the spectral functions $F_{\text{spec}}$ used to calculate the EBB radiances and the actual response of the filters at the time of the measurements. The problems with the spectral calibration referred to in section 5 mean that this mechanism cannot be ruled out at this stage, and the shape of the nonlinearity in Fig. 9 is very suggestive of an error of this type. An error in the filter profile used to generate the EBB radiances would lead to zero radiometric error at the temperatures of the SBB and CBB, where any profile will give a null radiance difference. The radiances corresponding to these temperatures are broadly consistent with the two points along the radiances axis at which the data in Fig. 9 exhibit zero radiance error. However, in the case of the filter wheel channels, the errors are predominantly linear—gain and offset errors—and in some elements of channels 40W and 50W, the shape of the radiometric error plot appears to combine both the linear and the “spectral”-type shapes.

It is clearly not possible to reconstruct on the basis of the radiometric data a unique consistent filter profile, so it useful to consider how much information is, in principle, present in the radiometric calibration data. The integration over the optics transmission function $F(n, \tilde{\nu})$, which we have been indicating with a bar over the radiance, is explicitly

$$\tilde{B}(T) = \int F_{\text{spec}}(\tilde{\nu}) B(\tilde{\nu}, T) d\tilde{\nu}$$

(20)

in the case of a spatially uniform radiance from the EBB. Since the filter spectral widths are all small ($2\%$–$6\%$ of center frequency) we can approximate the Planck function around the filter passband by a quadratic function:

$$B(\tilde{\nu}, T) \approx B(\tilde{\nu}_m, T) + \frac{\partial B}{\partial \tilde{\nu}}|_{\tilde{\nu}_m} (\tilde{\nu} - \tilde{\nu}_m)$$

$$+ \frac{1}{2} \frac{\partial^2 B}{\partial \tilde{\nu}^2}|_{\tilde{\nu}_m} (\tilde{\nu} - \tilde{\nu}_m)^2.$$  

(21)

If we insert (21) into (20), the linear term vanishes if we choose the origin of the expansion $\tilde{\nu}_m$ to be the mean filter wavenumber

$$\tilde{\nu}_m = \int F_{\text{spec}}(\tilde{\nu}) \tilde{\nu} d\tilde{\nu},$$

(22)

in which case the filtered radiance in (20) simplifies to

$$\tilde{B}(T) = B(\tilde{\nu}_m, T) + \frac{1}{2} \frac{\partial^2 B}{\partial \tilde{\nu}^2}|_{\tilde{\nu}_m} \delta \tilde{\nu}_{\text{rms}}^2,$$

(23)

where

$$\delta \tilde{\nu}_{\text{rms}}^2 = \int F_{\text{spec}}(\tilde{\nu}) (\tilde{\nu} - \tilde{\nu}_m)^2 d\tilde{\nu}.$$  

(24)

The implication of (23) is that only two filter parameters, the mean frequency $\tilde{\nu}_m$ and the width parameter $\delta \tilde{\nu}_{\text{rms}}$, influence the radiometry.

Thus, we have identified four potential error sources in the linearity data: offset and gain errors, which can arise from a number of sources including scan stray, and errors in the measured mean position and width of the spectral filter. We have determined that the error radiances plots, such as those in Figs. 9 and 10, can be fitted down to the noise level by small values of these error sources, but we have not yet determined whether the resulting values are physically reasonable in the light of what is known about the mechanisms generating these errors, nor have we yet studied the extent to which other mechanisms, including instrumental nonlinearity, as opposed to the apparent nonlinearity generated by the spectral errors, might also be present. These questions are the subject of ongoing work. The current operational data processing is based on the as-measured filter profiles, and the assumption of instrumental linearity, although in fact these assumptions are inconsistent at the 0.1% level.

### e. Noise

Estimates of the standard deviation of a single raw count for each signal channel were obtained from the low-order polynomial fits to sections of data as described above. These indicate the noise levels present at the digitizer output in the different channels. The standard deviation of an estimate of a limb radiance measurement $\sigma_K$ involves not only these noise estimates in the three signal counts $S$, $S_0(\theta_0)$, and $S_B$ in (18), but also the error in interpolating $S_0$ and $S_B$ to the measurement time of $S$, and estimates of the errors in the scan stray correction $C(\theta) = C(\theta_0)$ and $B_0(\theta)$. This error analysis is discussed further in Rodgers et al. (1996); here we concentrate on the measured noise in a single signal count, but express it in radiance terms by dividing by the gain.

Example results for the elements of channels 20W and 20P, calculated from a complete set of linearity data, are shown in Fig. 11, and a set of results for all channels averaged over the low-radiance end of this dataset are given in Tables 2 and 3. The outer elements of channels 10P, 20P, 50P, and 60P exhibited distinct
Fig. 11. Standard deviation estimates of signal counts as a function of input radiance for all four elements of channel 20W (upper) and channel 20P (lower).

anomalous noise features at intermediate and high radiances. These were also distinguishable in channels 20W and 50W. The majority of the elements, however, in both the wideband and the PM channels had radiance noises that showed no, or only a weak, correlation with the incident radiance. These wideband noises corre-
TABLE 2. Standard deviation (SD) estimates for a single calibrated wideband radiance, due to the atmospheric measurement only, averaged over signals of less than 0.2 R(T₀).

<table>
<thead>
<tr>
<th>Channel</th>
<th>E10</th>
<th>E11</th>
<th>E12</th>
<th>E13</th>
</tr>
</thead>
<tbody>
<tr>
<td>00W</td>
<td>1.66</td>
<td>1.60</td>
<td>1.59</td>
<td>1.67</td>
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<td>20W</td>
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<td>1.69</td>
<td>1.58</td>
<td>1.70</td>
</tr>
<tr>
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<td>9.23</td>
<td>9.35</td>
<td>10.3</td>
<td>10.5</td>
</tr>
<tr>
<td>31W</td>
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<td>8.89</td>
<td>9.02</td>
</tr>
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<td>2.25</td>
<td>2.36</td>
<td>2.49</td>
</tr>
<tr>
<td>33W</td>
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<td>9.28</td>
<td>10.0</td>
<td>10.5</td>
</tr>
<tr>
<td>40W</td>
<td>1.54</td>
<td>1.49</td>
<td>1.49</td>
<td>1.49</td>
</tr>
<tr>
<td>50W</td>
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<td>1.62</td>
<td>2.06</td>
<td>2.00</td>
</tr>
<tr>
<td>60W</td>
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<td>1.60</td>
<td>1.54</td>
</tr>
<tr>
<td>70W</td>
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<td>6.41</td>
<td>6.47</td>
<td>6.85</td>
</tr>
<tr>
<td>71W</td>
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<td>6.20</td>
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</tr>
<tr>
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<td>19.0</td>
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</tr>
<tr>
<td>73W</td>
<td>8.89</td>
<td>8.23</td>
<td>7.97</td>
<td>7.94</td>
</tr>
</tbody>
</table>

responded closely to the expected values due to digitization errors, while the PM channels had significantly higher gain and were background or detector limited. The detector noise was expected to vary with detector temperature; evidence for this from flight data is discussed by Rodgers et al. (1996).

f. Calibration stability

The linearity calibration with nominal instrument thermal conditions was repeated on four separate occasions, two pairs of runs separated by two weeks, and each pair consisting of a calibration run with increasing and decreasing EBB temperature. Example nominal calibrations for element 3 of channel 20W are illustrated in Fig. 12. Other channels behaved in a similar fashion. The general forms of the calibration curves were consistent between the different runs, consisting of the nonlinear feature referred to in section 6d, peaking at about 1 × 10^⁻³ R(T₀) at an input radiance of about 0.2 R(T₀). There appears to have been a small change in gain error between the earlier and later pairs of runs indicated by the increase in the calibration error curve at large radiance. The detailed form of the curve at low radiances, for example, the “blip” between input radiances 0.15 R(T₀) and 0.25 R(T₀) was, if anything, better correlated with the direction of the EBB temperature ramp (increasing radiance with time for the first run of each pair, and decreasing for the second). These small features are almost certainly attributable to the EBB thermometry or to the calibration of the thermometry data.

Three further linearity calibrations were made with perturbed instrument thermal conditions: with the instrument warm, with the detectors alone warm, and with the instrument cold. The range of conditions was roughly comparable with the range of orbital conditions in different seasons. Example calibrations for element 3 of channel 20W in the perturbed instrument states are compared with a nominal calibration in Fig. 13. The channel 20W gain calibrations had a noticeable sensitivity to instrument temperature, with the calibration curve for the warm run lying about 0.1% above the nominal, and the cold run about 0.1% below; the effect of detector temperature was much less significant.

7. Summary and conclusions

The key improvement in the ISAMS instrument over its predecessor SAMS (Drummond et al. 1980) is the provision of a closed-cycle cooler, allowing the detectors to operate at 80–90 K, leading to a greatly improved signal-to-noise ratio. As indicated above, it would be unrealistic to expect, and it has not proved possible, to reduce all systematic errors and calibration uncertainties by a comparable factor, so that the data analysis is now limited by manifest systematic effects. Three specific problems have been discussed in this paper: spectral profile uncertainties (section 5b), apparent nonlinearity (section 6d) and scan stray (sections 6b,c). The origins of these problems lie in certain key design decisions made early in the program.

One of these was the decision to place all the optical stops in the detector package: the field stop is the detector edge, the aperture stop is adjacent to the lens L4 and the spectral bandpass filter is located on the detector side of the lens L5. Since these optical components are all cooled, this placement leads to a very low unchopped background photon flux on the detectors, which was the key reason for choosing it. The aperture and field stop placement leads to a difficult alignment problem, with eight sets of detector packages to be co-aligned, which can only be done with infrared radiation and cooled detectors. This alignment is discussed

TABLE 3. Standard deviation (SD) estimates for a single calibrated PM radiance, due to the atmospheric measurement only, averaged over signals of less than 0.2 R(T₀).

<table>
<thead>
<tr>
<th>Channel</th>
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<th>E12</th>
<th>E13</th>
</tr>
</thead>
<tbody>
<tr>
<td>10P</td>
<td>2.93</td>
<td>2.77</td>
<td>2.95</td>
<td>3.94</td>
</tr>
<tr>
<td>20P</td>
<td>2.95</td>
<td>2.45</td>
<td>2.49</td>
<td>3.78</td>
</tr>
<tr>
<td>30P</td>
<td>24.3</td>
<td>23.7</td>
<td>26.6</td>
<td>28.6</td>
</tr>
<tr>
<td>31P</td>
<td>78.2</td>
<td>75.1</td>
<td>77.9</td>
<td>87.6</td>
</tr>
<tr>
<td>32P</td>
<td>—</td>
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<td>—</td>
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<td>33P</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>40P</td>
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<td>6.94</td>
<td>7.28</td>
</tr>
<tr>
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</tr>
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<td>72P</td>
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<td>—</td>
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</tr>
<tr>
<td>73P</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
Fig. 12. Four distinct linearity runs, with nominal instrument thermal conditions, for channel 2, element 3. Runs A and B: 9–12 September 1990, runs C and D: 24–26 September 1990. The EBB temperature was stepped up for runs A and C, down for runs B and D. The data in Figs. 9 and 10 are from run D.

Fig. 13. Four distinct linearity runs, with differing instrument thermal conditions, for channel 2, element 3. Run A: instrument warm; run B: detectors warm; run C: instrument cold; run D: nominal thermal conditions (run D of Fig. 12).
in Part II, but it was suggested above that the larger scan strays might result from some misalignment. The spectral filter is placed in a very fast optical beam, resulting in a filter profile that is significantly affected by the cone angle, and thus a spectral calibration that is sensitive to the uniformity of the test beam. In the event, this sensitivity was compounded by a design error in the monochromator, leading to the spectral uncertainty discussed above. Finally, the decision to measure the instrument linearity with a technique that required knowledge of the spectral bandpass profile meant that we cannot easily interpret the apparent nonlinearities that the measurements indicated. (There are direct methods of measuring linearity, using, for example, a test beam consisting of a small, constant amplitude chopped radiance summed with a variable background radiance, which directly measures the derivative of the radiance count with respect to radiance.) All of these points should be taken into account in the design of future instruments of this type.

This paper has concentrated on the spectral and radiometric aspects of the instrument calibration, which are linked by the problems discussed above. Part II discusses the remaining aspects of the preflight calibration: the coalignment of the detector packages, the measurement of $F_{\text{FOV}}$ for all channels, calibration of the angle encoders on the scan mirror, and the special calibrations required for a proper understanding of the PM channels. The effects of the calibration problems on, for example, the retrieval of atmospheric temperatures are discussed by Dudhia and Livesey (1996).

**Acknowledgments.** Many people contributed to the ISAMS program: the principal investigator is Fred Taylor (Oxford University), and the project manager during the calibration phase was Ray Turner (Rutherford Appleton Laboratory). Many members of Oxford Atmospheric, Oceanic and Planetary Physics, and RAL Atmospheric Sciences Division assisted in overseeing the calibration during periods of continuous operation; technical assistance came from Martin Clarke, Mick Johnson, Phil Hingston, Andy Clack, Bill Taylor, Jon Temple, Dave Toole, and Andy Pickering. The development of the calibration facility was the work of several people, including Barry Welsh and Andrew Sheppard.

The test team wish to express their particular debt to the late Steve Werrett, who was responsible for the design and realization of important aspects of the instrument, in particular the thermal system for cooling the eight separate detector packages, the command and data system, and the PCL software used for controlling the instrument and test equipment. He was also the popular leader of the night shift during periods of continuous working.

**REFERENCES**


