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SUMMARY

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An automatic system is described for use in determining the solar absorptance and thermal emittance of surfaces from spectral reflectance measurements. The system consists of two spectrophotometers used to make optical reflectance measurements, electronic digitizing equipment to record the data, and a high-speed electronic computer to calculate the desired results. Manual and automatic means of data reduction are compared to determine the reliability and reproducibility of the system. A significant decrease in data reduction time is realized with use of the automatic system.

Author

INTRODUCTION

Determination of the solar absorptance and thermal emittance of surfaces is of prime importance in many flight projects and research tasks now being carried out at the Langley Research Center. Since present theoretical methods of prediction of these parameters are inadequate, numerous hemispherical reflectance measurements are needed for proper spacecraft coating design and for the evaluation of the effects of the space environment on thermal-control coatings. Considerable time and effort were involved in reducing manually data of this nature and an automated system, such as the one described in this report, was thought to be desirable. The system involves two commercially available spectrophotometers used to make optical reflectance measurements, electronic digitizing equipment, designed by an industrial laboratory under contract to the Langley Research Center, to record the data, and a relatively common high-speed electronic computer to calculate the desired results. Manual and automatic methods of calculation of solar absorptance and thermal emittance are used to determine the system's reliability and reproducibility. A significant decrease in data reduction time is indicated with use of this automatic system.

SYMBOLS

R	reflectance
P	solar energy flux normalized to a value of unity
W	black-body emissive energy flux normalized to a value of unity
α	absorptance
ϵ	thermal emittance
λ	wavelength

Subscripts:

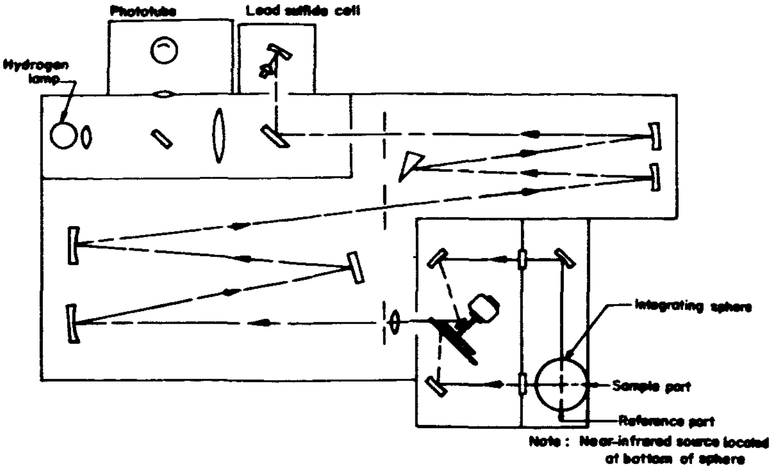
s	solar
λ	wavelength
i	ith element of a series

DETERMINATION OF SOLAR ABSORPTANCE

Spectrophotometer

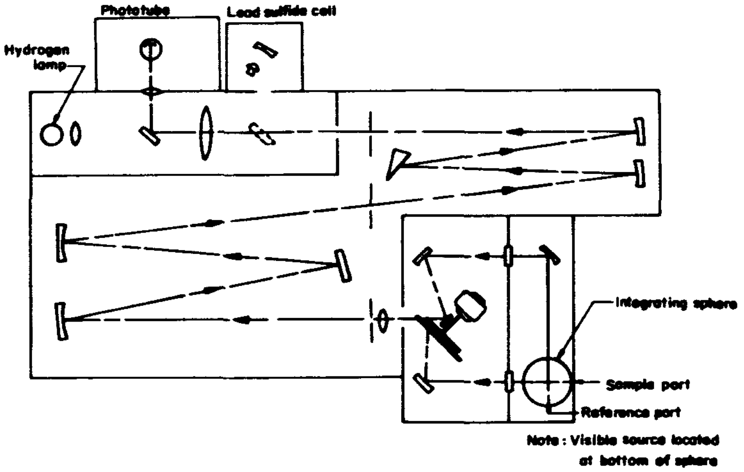
Total (specular plus diffuse components) hemispherical reflectance measurements used in the determination of solar absorptance were made with a double-beam recording spectrophotometer capable of automatically recording data between 0.22μ and 2.10μ on a linear wavelength scale. Radiation from a test sample and from a magnesium oxide reference standard is alternately detected and the ratio of the two quantities is automatically recorded.

The spectrophotometer provides both monochromatic and polychromatic illumination. Polychromatic illumination must be used in the near-infrared region (2.10μ to 0.70μ) because of the location of the lead sulfide detector (fig. 1(a)). In the visible (0.70μ to 0.36μ) and ultraviolet (0.36μ to 0.22μ) regions, either type of illumination may be used because of the interchangeability of source and detector locations. Reflectance data obtained by use of either type of illumination in these two regions are essentially the same. For convenience, polychromatic illumination is used in the visible region (fig. 1(b)) and monochromatic illumination, in the ultraviolet region (fig. 1(c)). For monochromatic illumination, radiation from a hydrogen lamp passes through a dispersing monochromator. The dispersed beam passes through a chopper and rotating mirror mechanism where it is divided into two beams, 90° out of phase, for later discrimination by the detector. The separated beams pass into the integrating sphere where they strike the test sample and the reference standard. The beams are reflected from the specimens onto the walls of



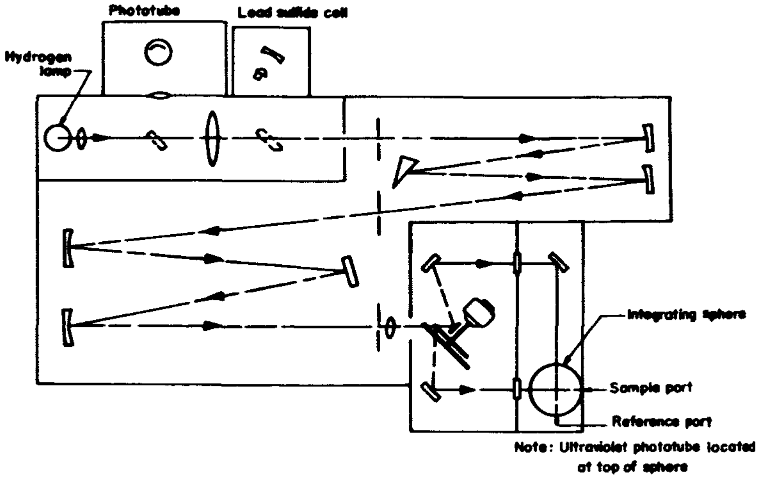
Note: Near-infrared source located at bottom of sphere

(a) Polychromatic near-infrared radiation.



Note: Visible source located at bottom of sphere

(b) Polychromatic visible radiation.



Note: Ultraviolet phototube located at top of sphere

(c) Monochromatic ultraviolet radiation.

Figure 1.- Solar-absorptance spectrophotometer radiation paths.

the integrating sphere and, after numerous reflections, reach the detector. For polychromatic illumination, the optical path is reversed. Light from a tungsten source is reflected in the integrating sphere and then strikes the test sample and the reference standard. The beams are then passed through the chopper and rotating mirror mechanism and recombined 90° out of phase. The recombined beam then passes through the monochromator to the proper detector.

The spectrophotometer employs a double monochromator consisting of a 30° fused silica prism in series with a 600-line-per-millimeter echelette grating, each with its own collimating mirrors and slit system. This combination provides the high resolving power characteristic of a grating spectrophotometer at long wavelengths plus the high optical efficiency and low scattered light characteristic of a prism monochromator. The resolving power of the monochromator is 1 Å in the ultraviolet and visible regions and 3 Å in the near-infrared region. The entrance, intermediate, and exit slits of the monochromator automatically adjust their width by means of a servomechanism to insure that constant light intensity from the reference beam reaches the detector.

The integrating sphere insures that radiation strikes both the detector and the specimens uniformly. It is coated on the interior with barium sulfate paint which has been found to have reflectance properties which are more stable with time than magnesium oxide, the standard coating (ref. 1).

A 100-percent-reflectance line is obtained by scanning over the entire wavelength range of the spectrophotometer while magnesium oxide reference standards cover both ports of the integrating sphere. Variations of this reflectance line from an established absolute reflectance line for magnesium oxide (fig. 3 of ref. 2) are compensated, wherever possible, by use of external manual programing The programer consists of a series of potentiometers which permit adjustment of recorded reflectance values by about 20 percent at 44 points over the wavelength operating range.

Digital Data Recording System

The function of the digital data recording system is to sense and digitize the wavelength screw and reflectance recorder shaft positions of the spectrophotometer and then to record them on punched cards. The system consists of photoelectric shaft-angle encoders, solid state control, storage, translation, and programing devices, and a card punch. A schematic of the system is shown in figure 2.

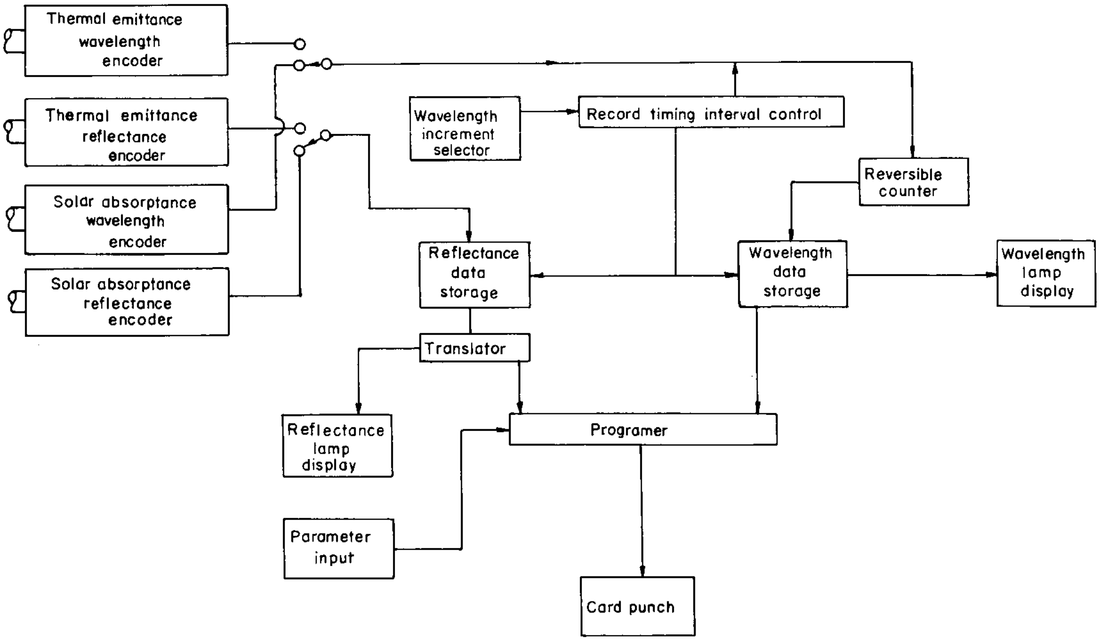


Figure 2.- Schematic drawing of the digital data recording system.

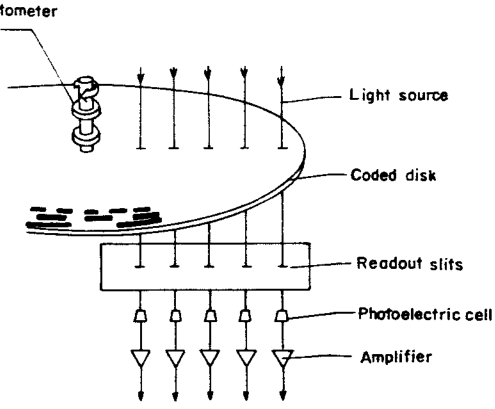


Figure 3.- A typical photoelectric encoder.

The encoders are simply photographically engraved, coded, glass disks with transparent and opaque segments, which are mounted on the shaft whose angular position is to be encoded. (See fig. 3 for sketch of typical encoder.) A narrow light beam illuminates the code pattern along a radial line. Readout slits, located underneath the glass disk, are radially alined with respect to the code pattern and view the illuminated radial segment of the disk. Directly behind is a bank of photocells which detect the amount of light passing through the slits. Depending on whether an opaque or transparent segment of the disk is between the lamp and one of the slits, the corresponding photoelectric cell will be either conducting or nonconducting. The code pattern consists of various combinations of on and off signals from the photoelectric cells to the storage units. The encoders are sealed in an airtight cover to prevent dust contamination.

For the wavelength function of the spectrophotometer, an incremental encoder is used which measures incremental angles rather than shaft position. Because the encoder accumulates output counts without periodically checking position against a reference point, a four-digit reversible counter is also used which follows the shaft position at all times by utilizing the incremental changes picked up by the photocells from the coded disk. The counter's register can be preset to any wavelength value by a series of decimal thumb wheel switches and will follow the encoder thereafter. Readout from the counter is transferred to the wavelength storage unit without destroying the information in the register. The incremental encoder generates 10 pulses per revolution, resulting in a least count corresponding to 0.001μ. A wavelength increment selector is provided in the system which can change the recording interval to any number up to 99 times the least count.

For the reflectance function, an absolute nonambiguous encoder is used in which a binary code eliminates ambiguities by having just one binary digit change at a time in the transition from one unique position to the adjacent position. The encoder has a resolution of 1000 parts per turn - that is, the encoder registers 1000 counts for a full-scale pen response of 0.00 to 1.00.

The recording interval control, which is regulated by the wavelength increment selector, insures that both the wavelength and the corresponding reflectance values are simultaneously transferred from the encoders into their respective storage units. Wavelength information is then directly transmitted to the lamp display and the programer. Reflectance information is first transmitted to the translator which converts the binary code used by the nonambiguous encoders to the decimal code used by the lamp display and the card punch. After translation, reflectance information is transmitted to the lamp display and the programer. The programer puts information into a format used by the card punch and generates timing pulses for its synchronization. The control, storage, translation, and programing units consist wholly of solid state transistorized modular circuit blocks and appropriate switches.

Raw data, in the form of punched cards, are fed into a common high-speed computer for reduction.

Theory

Solar absorptance values are calculated from reflectance data on the basis of the following equation:

$$\alpha_s = \frac{\int \alpha_\lambda P_\lambda \, d\lambda}{\int P_\lambda \, d\lambda} \tag{1}$$

where the limits of integration represent the full wavelength range of the solar spectrum and, therefore,

$$\int P_\lambda \, d\lambda = 1$$

The coatings tested are of sufficient thickness to make the transmittance zero so that $\alpha_\lambda = 1 - R_\lambda$. Equation (1) therefore reduces to

$$\alpha_s = 1 - \int R_\lambda P_\lambda \, d\lambda \tag{2}$$

In practice, the integral is approximated by discrete summations and equation (2) thus becomes

$$\alpha_s = 1 - \sum R_i P_i \, \Delta\lambda_i \tag{3}$$

Before conversion to an automatic system, manual solar absorptance calculations were made at increments corresponding to 1.0 percent of the solar energy in the wavelength region from 0.22μ to 2.10μ, using the spectral distribution reported by Johnson (ref. 3), so that each $P_i \, \Delta\lambda_i = 0.01$. The spectrophotometer wavelength range from 0.22μ to 2.10μ represents 95 percent of the solar spectral range. The maximum possible error in using this range is therefore 5 percent. The value of solar absorptance calculated for this wavelength range can thus safely be assumed to hold for the entire solar spectrum. Previous to summation, corrections were made to the reflectance readings at points where the preprogramed absolute reflectance of magnesium oxide, obtained by use of the

44 potentiometers, still differed from the absolute reflectance obtained by Zerlaut (ref. 2), who based his work on the results obtained by Middleton and Sanders (ref. 4). One of the differences is centered at 0.83μ and is due to unequal absorption by the aluminum mirrors in the spectrophotometer's optical system. The second difference is centered at 1.38μ and is due to preferential absorption of certain wavelengths by water vapor in the air.

When the digitizing system is used, wavelength and reflectance values are alternately punched onto computer cards at a constant wavelength increment. The electronic computer corrects for deviations in the absolute reflectance of magnesium oxide and then weights the reflectance value at each wavelength with the factor $P_i \Delta\lambda_i$ where P_i varies for each wavelength and $\Delta\lambda_i$ is constant. The corrected and weighted reflectance values are then summed, and the summation is subtracted from unity to obtain the solar absorptance.

DETERMINATION OF THERMAL EMITTANCE

Spectrophotometer

A second double-beam spectrophotometer, which is used to determine thermal emittance, permits measurements of reflectance from 2μ to 30μ on a nonlinear scale. It is used in conjunction with a hohlraum (heated cavity) attachment which is coated with nickel oxide ($\epsilon = 0.98$) to approximate a black body. The cavity temperature may be varied between 400° and 1100° C. The test sample can be water cooled to maintain its temperature anywhere between 0° and 100° C despite the higher ambient temperature in the cavity. The sample is irradiated diffusely by the wall of the hohlraum, which also acts as a black-body reference source. Both the reference beam and the sample beam are transmitted by a series of precision mirrors beneath the hohlraum through two different ports to the spectrophotometer. At this point, both beams are chopped 90° out of phase. The beams are then combined by another series of mirrors and pass into the monochromator. In the monochromator, the combined out-of-phase radiation passes through the entrance slit, is collimated by an off-axis parabola, and is then refracted by a fixed prism. The dispersed radiation is scanned automatically by a Littrow mirror which is controlled by the wavelength drive mechanism. The Littrow mirror returns the selected energy through the prism to the off-axis parabola which focuses energy through the exit slit and onto the thermocouple detector by means of a third series of mirrors. Figure 4 is a schematic diagram of the light path.

The monochromator employs interchangeable sodium chloride and cesium bromide prisms. The sodium chloride prism is used for measurements in the 2μ-to-15μ range and the cesium bromide prism, in the 15μ-to-30μ range. The entrance- and exit-slit widths of the monochromator can be made to vary according to the intensity of the reference beam so that the energy incident on the detector is kept relatively constant as the spectrum is scanned. The entrance slit is also curved to compensate for curvature of the slit image caused by the prism. The slits also control the bandwidth of the dispersed radiation seen by the detector and they thus determine the resolution available during a scan.

Digital Data Recording System

The digital data recording system performs the same functions for the thermal emittance spectrophotometer as for the solar absorptance instrument. Both spectrophotometers have independent encoders but share in common the control, storage, translation, and card punching devices. For the wavelength function, an incremental encoder is used which generates 100 pulses per revolution, resulting in a least count of 1/100 of a 360° turn of the monochromator-controlled drum. The nonambiguous encoder used for the reflectance function has a resolution of 1000 parts per turn and registers 1000 counts per shaft revolution of 320°.

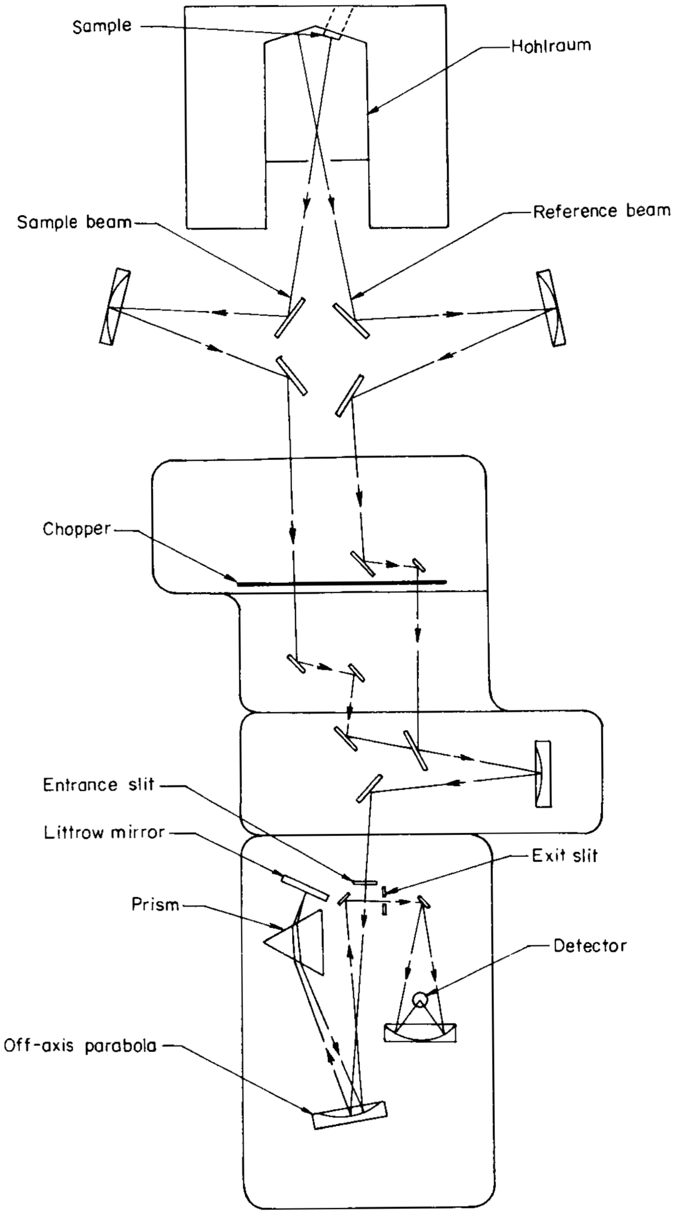


Figure 4.- Schematic diagram of the light path in the thermal emittance spectrophotometer.

Theory

Thermal emittance values are calculated from reflectance data on the basis of the following equation:

$$\epsilon = \frac{\int \alpha_\lambda W_\lambda \, d\lambda}{\int W_\lambda \, d\lambda} \qquad (4)$$

where the limits of integration range from zero to infinity and where $\alpha_\lambda = 1 - R_\lambda$. The integrals are approximated by discrete summations and equation (4) becomes

$$\epsilon = \frac{\sum (1 - R_i) W_i \, \Delta\lambda_i}{\sum W_i \, \Delta\lambda_i} \qquad (5)$$

For manual thermal emittance calculations, reflectance values were read at wavelength increments corresponding to 1.0 percent of the energy of a black body at the sample temperature, thereby making $W_i \Delta\lambda_i = 0.01$. These values were then corrected on the basis of a reference 100 percent line previously obtained. The value of $\Sigma W_i \Delta\lambda_i$ depends on the number of one-percent increments which can be found under a black-body curve in a particular wavelength region. For a 295° K black body, 55 of these points can be found between 2μ and 15μ, the sodium chloride prism range of the spectrophotometer. In this situation $\Sigma W_i \Delta\lambda_i = 0.55$.

Since the spectrophotometer records reflectance values on a nonlinear wavelength scale, the digital recording system was adapted to provide a record of reflectance at even increments of the turning of a monochromator-controlled drum. The spectrophotometer is calibrated against the known absorption bands of a polystyrene standard so that the wavelength as a function of the number of drum turns is known. A deck of punched cards, containing a table of drum-turn values, instructs the electronic computer to calculate only at points corresponding to 1.0 percent of the area under the curve of a black body of temperature equal to that of the test sample. A different table is provided for each prism and each sample temperature used. The reflectance data are corrected by dividing by the value of the reference 100 percent line at the same wavelength, and these corrected values are then subtracted from unity to obtain absorptance or emittance. The emittance values are summed and the sum is multiplied by the constant $W_i \Delta\lambda_i / \Sigma W_i \Delta\lambda_i$.

SYSTEM QUALIFICATION

Reliability

In order to check the reliability of the automatic digital data recording system, both manual and automatic methods were used to determine the solar absorptance and thermal emittance of eight samples of an amorphous phosphate thermal-control coating used on the Echo II (1964 4A) satellite (ref. 5). A comparison of the results (table I) shows that use of the automatic system yields data which differ from those obtained manually by less than 3 percent on a sample-by-sample basis and by less than 1 percent on the basis of mean values. These results indicate that the automatic system operates reliably, especially if the mean value of a number of samples is employed.

TABLE I.- THE SOLAR ABSORPTANCE AND THERMAL EMITTANCE OF THE ECHO II THERMAL-CONTROL COATING, OBTAINED BY MANUAL AND AUTOMATIC METHODS

Test sample	Solar absorptance			Thermal emittance		
	Manual method	Automatic method	Percent difference in values of methods	Manual method	Automatic method	Percent difference in values of methods
1	0.247	0.242	2.0	0.203	0.202	0.49
2	.246	.249	1.2	.207	.206	.48
3	.250	.243	2.8	.180	.179	.56
4	.259	.255	1.5	.167	.166	.60
5	.255	.251	1.6	.170	.169	.59
6	.255	.252	1.2	.181	.180	.55
7	.260	.263	1.2	.192	.191	.52
8	.237	.240	1.3	.197	.196	.51
Mean value	0.251	0.249		0.187	0.186	
Percent difference in mean value		0.80			0.53	

Reproducibility

As a check on the reproducibility, four independent determinations of the solar absorptance and thermal emittance were made on a ninth sample. The following results were obtained:

$$\alpha_S = 0.241 \pm 0.00039$$

$$\epsilon = 0.154 \pm 0.00071$$

These small mean deviations show that the automatic system yields highly reproducible results.

Data Reduction Time

In a normal workday, 10 to 12 samples can be tested on either of the two spectrophotometers, with or without the automatic system. An experienced person can reduce these data to solar absorptance or thermal emittance at the rate of about 1 scan per hour. With the use of the automatic system, this person's contact time for these same 10 or 12 samples is reduced to approximately 1 hour - the time necessary to transport the raw data to the electronic computer on one day and to return for the final result the next day. The computer operator's contact time for these calculations is on the order of 30 minutes. Therefore, an estimated 85 percent saving in data reduction time is obtained by use of the automatic system.

CONCLUDING REMARKS

An automatic system for determining the solar absorptance and thermal emittance of surfaces from spectral reflectance measurements has been described. The description indicates that use of this system is a conceptually uncomplicated and reliable means of reducing the large amounts of data needed to determine the thermal radiation characteristics required for proper design of spacecraft coatings. Use of the automatic digital data recording system yields an estimated 85 percent saving in data reduction time.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., March 18, 1965.

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