NASA TECHNICAL NOTE

NASA TN D-4594

c. 1

NASA TN D-4594

STAR TRACKER CALIBRATION

by Lawrence T. Draper

Goddard Space Flight Center

Greenbelt, Md.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1968

STAR TRACKER CALIBRATION

By Lawrence T. Draper

Goddard Space Flight Center
Greenbelt, Md.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

ABSTRACT

Optical star tracker calibrations varied among companies in the industry by as much as 250 percent. A calibration procedure has been developed which relates a standard of spectral irradiance to real stars by laboratory measurements and computations. Initial results from trackers calibrated for the Aerobee Sounding Rocket Program indicate a calibration accuracy on the order of 15 percent.

CONTENTS

LIST OF SYMBOLS

B	=	Apparent intensity of a point source.
m	=	Apparent stellar magnitude outside the earth's atmosphere.
$V(\lambda)$	=	Relative spectral response of the standard visual observer normalized to unity at the wavelength of peak response, $V(\lambda_p)$.
K_m	=	Constant normalization factor of the function $V(\lambda)$ at λ_p. The units of K_m are lumens/watt.
$H_1(\lambda)$	=	Spectral irradiance or irradiance per unit wavelength interval produced by Source 1.
I	=	Effective intensity of a point source.
$R(\lambda)$	=	Relative spectral response of a photoelectric instrument normalized to unity at the wavelength of peak response $R(\lambda_p)$. The response includes the spectral effect of all lenses, mirrors or filters in the optical path.
$R_1(\lambda)$	=	Relative spectral response of Instrument 1.
K_d	=	Radiant sensitivity is the constant normalization factor of the function $R(\lambda)$ at λ_p. The units of K_m are amperes/watt.
AOV	=	Classification of a star whose spectral class is AO and whose luminosity class is V.
$H_{AOV}(\lambda)$	=	Spectral irradiance produced outside the earth's atmosphere by an AOV type star.
S-4, S-20	=	Designations adopted by the electronics committee of the Electronic Industries Association to describe the nominal sensitivity as a function of the wavelength of cesium-antimony and trialkali photocathode surfaces respectively. [JEDEC Publication No. 50 "Relative Spectral Response Data for Photosensitive Devices (S-Curves)", Electronic Industries Association, Washington, D. C.].
U, B, V	=	Apparent magnitudes outside the earth's atmosphere in the UBV System of Stellar Photometry established by H. L. Johnson of the University of Arizona. (Johnson, H. L. and Morgan, W. W., Astrophy. J. 117:313, 1953).

STAR TRACKER CALIBRATION

by

Lawrence T. Draper

Goddard Space Flight Center

INTRODUCTION

It became apparent during the development of star trackers for various programs that there was no industry-wide star tracker calibration procedure. The several companies involved developed their own calibration methods, and while these were reasonable and consistent within themselves, they were all different (Reference 1). Consequently, there was general disagreement about what represented a real star and how a tracker should be irradiated for signal-to-noise ratio measurements during acceptance testing.

A star tracker calibration procedure was developed over a period of time at Goddard Space Flight Center, and has been adopted to eliminate this ambiguity. This procedure involves a light source which is used as a standard of irradiance and computer programs which relate this standard source to real stars. The initial results of flight tests indicate that the calibration accuracy is within 15 percent. The purpose of this paper is to describe this calibration procedure.

STANDARD LIGHT SOURCE

The irradiance standard which was designed and developed (Reference 2) at The National Bureau of Standards (NBS) is shown in Figure 1. It consists of a portable light tight box, a projection lamp, an opal diffuser, filters, and an output aperture 20 mils in diameter. The spectral irradiance produced by the source $H_s(\lambda)$ has been measured from 3500A to 8500A and has a peak around 4300A. There is energy beyond 8500A, but this is not troublesome because the currently used detectors have no response in this region. If detectors with responses beyond 8500A are used in the future, the same calibration procedure can be used simply by extending the defined spectral

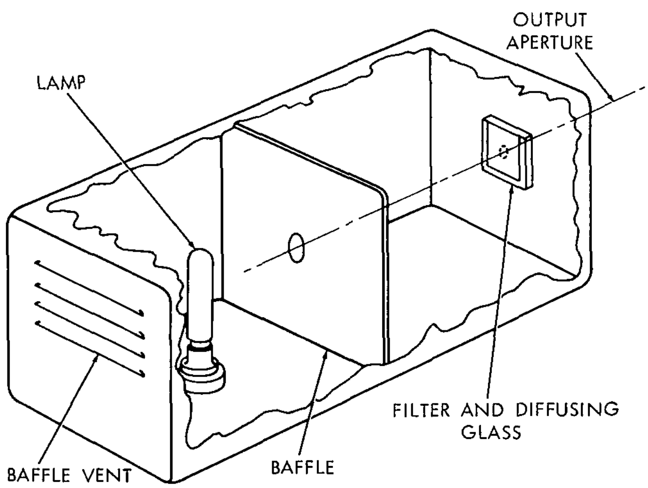

Figure 1—Laboratory standard of irradiance.

irradiance of the source to include all the wavelengths to which the detector is sensitive.

The described source is attractive because it is portable, easy to use, and has reasonable amounts of energy below 4500A (Figure 2). The shape of the absolute spectral irradiance function is of no importance to the calibration method; however, it is important to irradiate the receiver with energy as far into the blue as possible. When an unfiltered tungsten source is used for calibration purposes, for instance, the instrument response to very blue sources such as O or B type stars is only approximated. Note, in Figure 3, that the unfiltered tungsten source which simulates a 2nd visual magnitude star has very little energy below 4500A.

Several other types of irradiance standards considered by NBS in this program were all discarded for various reasons.

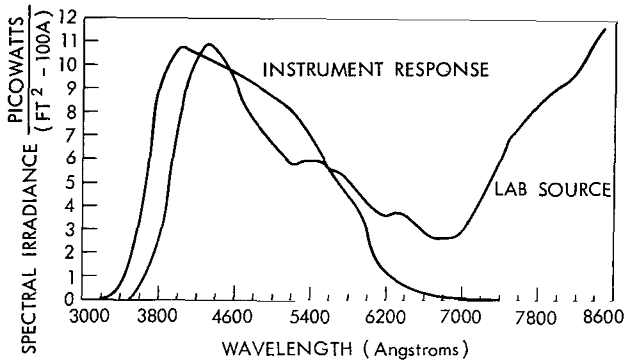

Figure 2—Absolute spectral irradiance produced by laboratory source when used to simulate 2nd visual magnitude star and nominal relative spectral response of S-4 instrument including optics.

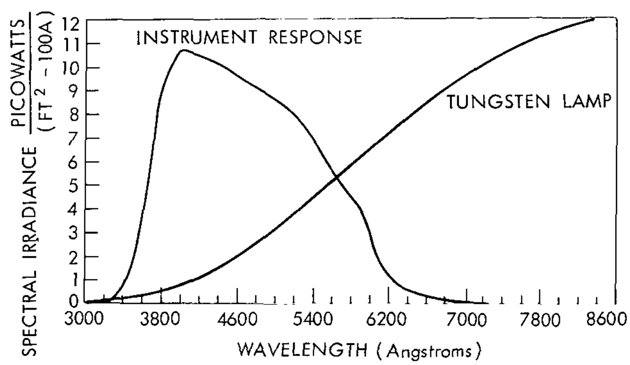

Figure 3—Absolute spectral irradiance produced by 2850°K tungsten source (including spectral emissivity of tungsten) when used to simulate 2nd visual magnitude star and nominal relative spectral response of S-4 instrument including optics.

MAGNITUDE EQUATION

The light source is related to real stars by means of computations with the equation for stellar magnitudes. This equation derives from the fact that classically the ratio of apparent intensity between successive magnitudes was defined as the fifth root of one hundred, or 2.512. If B_1 is the apparent intensity of a star of magnitude m_1 and B_2 is the apparent intensity of a star magnitude m_2, then

$$\frac{B_1}{B_2} = 2.512^{(m_2 - m_1)}$$

or

$$\log \frac{B_1}{B_2} = (m_2 - m_1)\ 0.4$$

or, finally,

$$m_1 - m_2 = -2.5 \log \frac{B_1}{B_2} .$$

It is common practice in photometry to express the effect produced by a point source of light in terms of the illumination produced at the observers eye (Reference 3). Therefore, the quantity "apparent intensity" is expressed as *illumination,* which is incident luminous flux per unit area, and must be distinguished from "luminous intensity" which is expressed as *emitted luminous flux per unit solid angle.*

The apparent intensity B_1 of a specific star is, then,

$$B_1 = K_m \int H_1(\lambda)\ V(\lambda)\ d\lambda \tag{1}$$

where $H_1(\lambda)$ is the absolute spectral irradiance produced by Star No. 1 at the observers eye, $V(\lambda)$ is the relative luminous efficiency of the standard eye response normalized to unity at 5500A, and K_m is the luminous efficiency of radiation at 5500A. The apparent intensity is then a measure of the eye's ability to utilize the total radiant power impinging on it.

In order to generalize this concept sufficiently to encompass photoelectric receivers as well as the eye, the term "effective intensity" is used in place of "apparent intensity". The effective intensity, I of Star No. 1 is

$$I_1 = \int H_1(\lambda)\ R(\lambda)\ d\lambda , \tag{2}$$

where $H_1(\lambda)$ is the absolute spectral irradiance produced by Star No. 1 at the objective lens of the receiver, and $R(\lambda)$ is the relative spectral response of the receiver normalized to unity at the peak of its response. $R(\lambda)$ is the total receiver relative spectral response, which includes the response of the photosensitive surface and the spectral effects of any optics or filters. The effective intensity is then a measure of the detector's utilization of the total radiant power impinging on it. The absolute spectral response of the receiver is equal to $K_d R(\lambda)$ where K_d is the normalization factor of the detector in amperes per watt at the wavelength of the peak response of $R(\lambda)$. If A is the area of the receiver objective lens, then $K_d A I_1$ is the anode current generated when the receiver is being irradiated by Star No. 1.

Replace apparent intensities by effective intensities; the magnitude equation can then be written as

$$m_1 - m_2 = -2.5 \log \frac{K_d \int H_1(\lambda)\, R(\lambda)\, d\lambda}{K_d \int H_2(\lambda)\, R(\lambda)\, d\lambda} . \tag{3}$$

The radiant sensitivity term, K_d, cancels, therefore it is only necessary to know the relative spectral response of the instrument, $R(\lambda)$.

The magnitude equation only defines a relative scale of effective intensity ratios and magnitude differences. A zero point for this scale is defined by always using the absolute spectral irradiance of a standard star, as seen above the atmosphere, in place of the function $H_2(\lambda)$ in Equation 3 and requiring that the magnitude of this standard star be the same for all receivers. The adopted standard is an AOV star whose photoelectric V magnitude is zero, which is consistent with the standard definition used to set the magnitude scale zero point in stellar photometry. Since this standard has the same magnitude for all receivers, it follows then that m_2 in Equation 3 is always zero and the final form of the magnitude equation is

$$m_1 = -2.5 \log \frac{\int H_1(\lambda)\, R(\lambda)\, d\lambda}{\int H_{AOV}(\lambda)\, R(\lambda)\, d\lambda} ; \tag{4}$$

here m_1 is the magnitude of the source $H_1(\lambda)$ as seen by receiver $R(\lambda)$.

STANDARD AOV STAR

The justification for the adopted magnitude zero point and the adopted absolute spectral energy distribution of the standard star have been discussed in detail by R. E. Wilson of the University of South Florida*. Briefly, the relative spectral energy distribution of Vega was used for the relative spectral energy distribution of the standard star. Oke and Hunger's data were used from 3700A to 8500A (References 4 and 5) and Bahner's data from 3196A to 3700A (Reference 6). The resulting relative spectral energy distribution was fitted to absolute measures made by Willstrop (Reference 7) and checked against those of Kharitonov (Reference 8) to obtain an absolute spectral energy distribution. The adopted standard AOV zero magnitude star is shown in Figure 4.

RECEIVER CALIBRATION PROCEDURE

The calibration procedure is suggested from the form of Equation 4. Notice that the integrals in the magnitude equation are proportional to the phototube anode current that an instrument would

*Wilson, R. E., "The S-4, S-11, and S-20 Magnitudes of a Star Simulator for the OAO", Goddard Space Flight Center Document X-732-68-28, January 1968.

produce if the objective lens of the instrument were being irradiated by the respective sources $H_{AOV}(\lambda)$ and $H_1(\lambda)$. The instrument anode current when viewing the standard star $H_{AOV}(\lambda)$, is a constant, K_1, for any given receiver. Therefore, Equation 4 can be rewritten as

$$m = -2.5 \log \left[\text{anode current when viewing } H_1(\lambda)\right] + K_1 . \qquad (5)$$

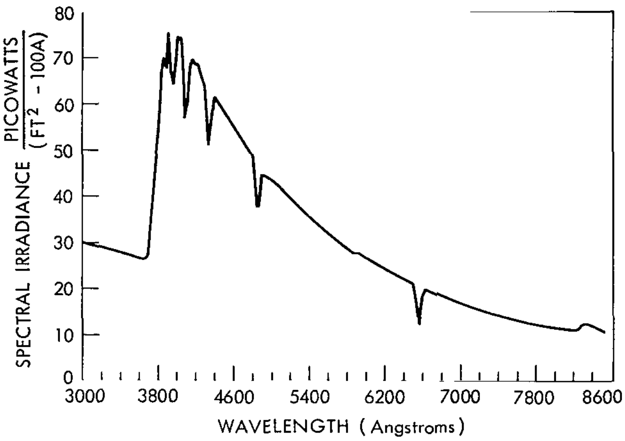

Figure 4—Absolute spectral irradiance of a zero magnitude AOV star as seen above the atmosphere.

Since m is a linear function of the log of the anode current, it is only necessary to determine the coordinates of one point of Equation 5 to allow the construction of a calibration curve. The coordinates of this point (magnitude, anode current) are determined for a receiver with relative spectral response $R_1(\lambda)$ as follows: The receiver anode current is measured when the standard source $H_s(\lambda)$ is used to irradiate the receiver objective lens, and the magnitude that the standard source $H_s(\lambda)$ presents to receive $R_1(\lambda)$ is computed by solving Equation 4 rewritten as

$$m = -2.5 \log \frac{\int H_s(\lambda)\, R_1(\lambda)\, d\lambda}{\int H_{AOV}(\lambda)\, R_1(\lambda)\, d\lambda} .$$

With the coordinates of one point thus determined, a straight line calibration curve can be drawn on semi-log paper for receiver $R_1(\lambda)$. One can now sight a source with an arbitrary spectral content, measure the anode current, and determine the receiver magnitude of that source from the calibration curve.

RECEIVER MAGNITUDES

Obviously the magnitude of source $H_1(\lambda)$ in Equation 4 depends on the receiver response. Therefore the term "magnitude" must always be qualified to indicate which receiver is being used. There is enough variation in the relative spectral response of any given type of phototube that it is necessary to be more specific than merely referring to S-4 or S-20 magnitudes. Actually, it is necessary to consider magnitude units for each individual instrument, i.e., "receiver magnitudes".

The calibration defined thus far is not complete enough for star tracker work because the instrument is calibrated in terms of receiver magnitudes which pertain only to the specific instrument being calibrated, and all of the star catalog data are given in different incompatible magnitude systems.

If the spectral energy distribution of each star which might be viewed with the star tracker were known, it would be an easy task to put each of these functions in Equation 4 in place of $H_1(\lambda)$ and calculate the magnitude of each star for any arbitrary receiver $R(\lambda)$. This is not generally possible because the spectral energy distributions of the twenty or thirty brightest stars are not yet available with sufficient accuracy.

A method has been developed by P. B. Davenport* for transforming from Johnson's *UBV* magnitude system to magnitudes for any arbitrary receiver response in the 3000A to 8000A region. Briefly, the transformation involves approximating the absolute spectral energy function of a star from its *UBV* magnitudes and then using this function in Equation 4 to compute the star's receiver magnitude for any arbitrary receiver. Knowledge of the magnitude of any target star in terms of receiver magnitudes in addition to the calibration curve of receiver magnitudes vs log of anode current does constitute a complete calibration.

COLLIMATED LIGHT SOURCE CALIBRATION PROCEDURE

When the tracker to be calibrated has optics which are prefocused at infinity it is often not possible to use the point source irradiance standard directly. In this case it is necessary to activate the tracker with a collimated source whose calibration can be traced to the point source standard. The transfer of the calibration from the point source to the collimated source is accomplished as follows: (1) a transfer photometer with a known relative spectral response is calibrated with the point source using the receiver calibration procedure described above; (2) the relative spectral energy distribution of the collimated source $H_c(\lambda)$ is measured; and (3) the collimated source is viewed with the transfer photometer. The magnitude of the collimated source in terms of transfer photometer magnitudes is obtained from the transfer photometer calibration curve resulting from step one.

Equation 4 can be rewritten as

$$m_t = -2.5 \log \frac{c \int H_c(\lambda)\, R_T(\lambda)\, d\lambda}{\int H_{AOV}(\lambda)\, R_T(\lambda)\, d\lambda}, \tag{6}$$

where $H_c(\lambda)$ is the collimator spectral energy distribution normalized to unity at some arbitrary wavelength, $R_T(\lambda)$ is the relative response of the transfer photometer, m_t is the transfer photometer magnitude of source $H_c(\lambda)$ resulting from step three above, and c is the absolute monochromatic flux of the source at that wavelength where the function $H_c(\lambda)$ is normalized to unity.

*Davenport, P. B., "The Approximation of Stellar Energy Distributions and Magnitudes from Multi-color Photometry," Goddard Space Flight Center Document X-542-68-120, April 1968.

Equation 6 can now be solved for c, determining the function $cH_c(\lambda)$ which is the absolute irradiance of the collimated beam dimensionally consistent with the function $H_{AOV}(\lambda)$ in Equation 6. The collimated light source is now calibrated and can be used instead of the point source in the basic receiver calibration procedure described above.

The relative spectral energy distribution of the collimated source varies as a function of lamp voltage; therefore, if lamp voltage is used to control the collimator intensity, the spectral energy distribution must be determined for each voltage used. More frequently the lamp voltage is held constant and the intensity is varied with neutral density filters. Since no neutral density filter is *truly* neutral, the spectral transmission of each filter must be measured and its effect on the spectral energy distribution must be included in the collimator function.

CALIBRATION ERRORS

No detailed error analysis has yet been made, but a worst case approximation can be determined by taking the root-sum-square error of each of the parts of Equation 4. The absolute spectral energy distribution of the standard star, $H_{AOV}(\lambda)$ is known within 2% over the wavelength range of interest (Reference 4); the absolute spectral irradiance produced by the standard light source at any specific distance is known within 6 percent (Reference 2); and the relative spectral response of the instrument receiver can be measured within 4 percent (Reference 9). The RSS error of the procedure is ±7.5 percent. However, an additional error, which does not appear in Equation 4, must be assigned to this calibration: the instrumental error involved in measuring the receiver anode current when its objective lens is being irradiated by the laboratory light source. This error should be less than 3 percent; therefore, the total RSS error involved in an instrument calibration using the point source standard of irradiance is on the order of ±8 percent.

An instrument calibrated with a collimated source as described above would have two additional sources of error: the determination of the relative spectral energy distribution of the collimated source, which can be measured within 4 percent*; and the instrumental error involved in measuring the anode current in the intermediate transfer of calibration from point source to collimated source, which is an additional 3 percent. The total estimated RSS error in this instance is approximately ±9.5 percent.

VERIFICATION OF CALIBRATION

Star trackers used in the Aerobee Sounding Rocket Attitude Control System were calibrated by the procedure described, and a star catalog was computed for each flight in terms of "receiver magnitudes". The star magnitude telemetry data for each target star allowed a comparison between the predicted magnitude and the measured data. Many additional data must be collected for complete verification, but information from four different flights show an RMS error of less

*Goebel, D., Private Communication with D. Goebel of the Optics Metrology Branch of the National Bureau of Standards, Gaithersburg, Maryland.

than 0.1 magnitude with a maximum error of 0.14 magnitude from a total of 7 targets. This RMS error includes errors from the telemetry and the receiver magnitude computations as well as the errors involved in the instrument calibration.

FUTURE PLANS

It is planned to continue development work in several areas related to star tracker calibration. A research effort is being conducted at NBS to improve the accuracy of the absolute spectral irradiance of the laboratory source and to extend its wavelength region to allow calibration of semi-conductor photoelectric devices. The spectral irradiance of the standard AOV star will also be extended for this purpose. In addition, a detailed error analysis will be conducted to determine which parameters of the calibration procedure must be improved to realize the greatest improvement in the overall calibration accuracy. Finally, work will continue in the Aerobee Program to obtain more flight data.

ACKNOWLEDGMENTS

The author wishes to acknowledge the contributions to the development of this calibration procedure by Lionel Chernoff, formerly of the National Bureau of Standards; Robert Wilson, of the University of South Florida; and Walter Raskin and Paul Davenport of Goddard Space Flight Center.

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland, January 1968
831-31-75-01-51

REFERENCES

1. Draper, L. T., "An Approach to Standardizing Star Tracker Calibration," Technical Paper No. 1.4.4.-1; *Proceedings of the Twelfth East Coast Conference on Aerospace and Navigational Electronics,* sponsored by the IEEE, October 1965, Baltimore, Maryland.
2. Chernoff, L., and Sirota, D., "An Artificial Star Source for the OAO," National Bureau of Standards Report 8619 and Supplement.
3. Walsh, J. W. T., "Photometry," Third Edition, New York: Dover Publications, Inc., 1958, page 475.
4. Oke, J. B., "Standard Stars for Photoelectric Spectrophotometry," *Astrophys. J.* 131(2):358-362, March 1960.
5. Hunger, K., "Die Atmosphäre des A O-Sternes Alpha Lyrae," *Zeit. für Astrophysik* 36(1):42-97, 1955.

6. Bahner, K., "Energy Distribution in the Spectra of Early-Type Stars," *Astrophys. J.* 138(4):1314, November 15, 1963.

7. Willstrop, R. V., "Absolute Measures of Stellar Radiation," *Monthly Notices of the Royal Astronomical Society* 121(1):17-40, September 1960.

8. Kharitonov, A. V., "Extra-Atmospheric Spectrophotometric Standards Energy Distribution in the Spectra of Selected Stars in CGS Units," *Soviet Astronomy* (English) 7(2):258-266, September-October 1963.

9. Information Sheet on Spectral-Sensitivity Measurements Available from Photometry and Colorimetry Section, Metrology Division, National Bureau of Standards, Gaithersburg, Md., December 27, 1965.

NASA-Langley, 1968 —— 21

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546

OFFICIAL BUSINESS

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

030 001 4[illegible] 51 3[illegible]S 6[illegible]134 00903
AIR FORCE [illegible] LABORAT[illegible]Y/[illegible]L/
KIRTLAND [illegible] BASE, [illegible] MEXICO 8711[illegible]

ATT [illegible] [illegible]
LIBRARY /[illegible]L[illegible]L/

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546