A SURVEY OF METHODS FOR MEASURING THERMALLY INDUCED

DISTORTIONS OF TEST ARTICLES UNDERGOING SOLAR THERMAL VACUUM TEST

R. D. Rempt
Martin Marietta, Denver, Colorado

ABSTRACT

Recent trends in space vehicle test requirements have called for precise knowledge of small thermally induced distortions experienced either by various points on the vehicles or by deviations of surfaces from a known shape during solar thermal vacuum test. Various methods of gathering such information during test are presented in this paper. State-of-the-art application of both photographic and real time observation are discussed. The relative merits of each of the methods are compared and evaluated in their applications to different types of test articles and situations. Magnitudes of thermally induced distortions which may be expected to be routinely measurable by the various methods are presented and compared.

INTRODUCTION

In order to select the best methods of precisely measuring thermally induced distortions in test articles for various configurations and conditions, a survey of the current state-of-the-art was made. The survey includes investigation of the applicability of all reasonable methods of performing the measurements. Each method is discussed, and its applicability evaluated with respect to measurement type, test article type and environment, along with the resolution which can be ascribed to the particular instruments. A matrix summarizing the applicable channels of each method is presented as a conclusion.

PHOTOGRAMMETRY

In the last decade and a half, nontopographic photogrammetry has been developed to routinely record and measure small distortions. Cameras suitable for operation inside of thermal vacuum chambers have been developed and used with a good degree of success. Owing to the capability of precisely locating a point on a developed plate with a comparator, accuracies of one part in sixty thousand of the largest diameter of the test article are routinely achievable. These, of course, are relative measurements. If absolute measurements are required, a suitable gauge bar is necessary which must be placed properly within the field of view of the cameras, and which will not change appreciably over the temperature range of the test.

The most important immediate application of photogrammetry to thermal vacuum testing is where knowledge of an entire surface is of interest. A photograph records the position of all points on the surface instantaneously whether the surface is in thermal equilibrium or not. No other methods can

record the changing of a flexible surface, but only the initial and final
positions when thermal equilibrium is established. Also, any line of sight
application will only give information concerning a few points rather than
the whole surface at once. It is often of interest to know how much a sur-
face such as an antenna mesh deviates from a known preset configuration such
as a paraboloid of revolution. Photogrammetry provides this knowledge accu-
rately and routinely. Also, a permanent record is taken which may be recal-
led later for additional analysis without having to rerun an expensive test.

The photogrammetric process depends on affixing of a large number of
adhesive targets to the surface of the test article. Test articles which
cannot tolerate such targets or are not capable of being distinctly targetted
in some other way, are generally not measurable by photogrammetric means.
Presently, NASA is investigating the possibility of mensurating the thermo-
reflective tiles on the STS orbiter for distortion after each flight by
photogrammetric means.

The greatest drawback of this process is that the data are not available
in real time. After the plates are developed, several days are required to
measure and reduce the data. This process must be performed by highly
trained and experienced personnel, and therefore photogrammetric capabilities
are most easily acquired through a subcontractor. If many tests are to be
made, development of the capability in-house may be cost effective, but due
to the experience required on the learning curve, such development will not
come quickly.

DIRECT LINE-OF-SIGHT METHODS

For purposes of this discussion, these types of measuring techniques will
be confined to direct optical line of sight established by instrumentation
sighting through a window in the thermal vacuum chamber. The requirement of
a window adds expense for optical flatness as well as for the thickness
required for vacuum safety. All instruments employing optical line of sight
detect movement perpendicular to the line of sight. This requires that no
surfaces which bend or otherwise redirect the line of sight be used unless
their movement is independently monitored. Since the instrumentation required
to monitor the beam bending apparatus is equivalent to the instrumentation
making the measurements of interest, it is hardly advantageous to bend the
beam unless geometry requires it. Hence, the term "direct line of sight".
This is demonstrated in figure one.

The great advantage of direct line of sight (DLOS) is that initial
coarse alignment may be achieved quite easily by personnel outside the vacuum
chamber. There are two requirements to ensure meaningful DLOS performance.
The first is that all instrumentation must be mounted on stable fixtures
which are not disturbed by the movement of personnel and equipment outside
the chamber. The second is that the test article has distinctly identifiable
and precisely locatable "targets".

For measurements where orientational changes only are of interest,
theodolites may be used. Good instruments have resolutions 1 x 10^{-5} rad
for the manual types and 3 x 10^{-5} rad for the electronic digital types.

The measurements are made by sighting on a suitable optical target or auto-collimating with the theodolite on an optical mirror. One optical target or one mirror is necessary per rotational axis of interest.

For measurements of translation of distinct points in three-dimensional space, there are several ways of obtaining the information. A jig transit square mounted on a tooling bar with an optical micrometer may be travelled parallel to the absolute measurement of interest. Two instruments mounted on mutually perpendicular tooling bars would be required for measurement in the plane perpendicular to the DLOS. A third instrument could be sighted perpendicular to the DLOS of the first two to recover information from the remaining axis. Such a setup would require at least two vacuum windows mounted in planes at right angles. Since tooling bars are so large and massive, continuous checks are necessary to confirm that the bars themselves are not moving with respect to the vacuum chamber. Resolution of a good optical micrometer is 5×10^{-6} M.

If sufficient field of view is available through windows, measurements may be made by triangulation with the odolites. Manual theodolites may be used, but the calculations required with their use are cumbersome. Digital theodolite systems have the advantage of computer interface which facilitates computation of positions of points in space once calibration is set. If a temperature independent gauge bar is not available, a normal gauge bar may be placed outside the chamber for purposes of calibration with no loss of accuracy. An important advantage of the digital theodolite is that angles are "read" automatically and the values transferred to the computer, relieving the operator of reading a vernier, thus greatly decreasing his eye fatigue.

An interesting application of theodolites may be made when the angular measurements of interest are quite small. In such a case, a lens system may be mounted on the telescope of the theodolite to convert it to a remote "microscope". In this instance, care must be taken to affix fine enough marks or scratches on the test article.

The two draw backs of all DLOS applications are optical vacuum windows which are quite expensive, and training of operating personnel.

An application of theodolites to perform stereotriangulation mensuration of a test article is shown in figure two.

LASER INTERFEROMETRY

In contrast to DLOS instruments, laser interferometers are capable of measuring CHANGE IN OPTICAL PATH LENGTH, which is parallel to the optical path. Since the capability of counting interference fringes is the fundamental principal of detection, resolutions of fractions of optical wavelengths are possible. Typical resolutions of $\lambda/8$ are routinely achievable. This translates into about 8×10^{-8} M for a Helium-Neon laser, which is the most commonly used for applications of this type. Since change in optical path is simply twice the actual "distortion" along that path, real time readout of actual distortion values is possible. In most cases, dynamic

thermal distortions may be continuously monitored in real time, since inter-
ferometers may be rigged to count fringes equivalent to a distortion rate of
several meters per minute.

Although it is not quite a "drawback", a complication of laser inter-
ferometry is that a separate beam must be used to detect change in path for
each path of interest. If rotation is of interest, since it takes place in a
plane, at least two beams are required for measurement about only one axis.
Also, since change along the entire path is detected, if the beam must be
"bent", the movement of the beam bending apparatus must be monitored by an
additional beam and subtracted out in order to make the measurement of inter-
est meaningful. Figure three shows a typical laser setup to measure the
distortion of a rectangular parallelapiped. All beams may be brought in
through the same window, (allowing measurement of "hidden" points), or
through different windows. If a multichannel interferometer is used, all
measurements may be simultaneously monitored in real time. The best way to
take advantage of all data is to interface with a computer and reconstruct
the motion of the test article as a whole from the path length changes de-
tected by the interferometers.

The expense of the laser head or heads and the interferometers with their
associated electronic counting equipment and computers are the only drawback
to their wholesale application for distortion measurements. If the interfero-
meters are designed properly, the vacuum windows may be of only average opti-
cal quality without affecting performance appreciably. The magnitudes of the
distortions, however, must be kept quite small, < 1 cm to prevent the beams
from being "lost" from the aperture of the retroreflectors. It would be
impractical to attempt to mensurate a large number of points to "cover" a
whole surface due to the amount of beams required along with the sophistica-
ted monitoring equipment for each. These methods are best applicable there-
fore to structural assemblies such as trusses rather than to surfaces. Flex-
ible members cannot be measured by laser interferometers since the retro-
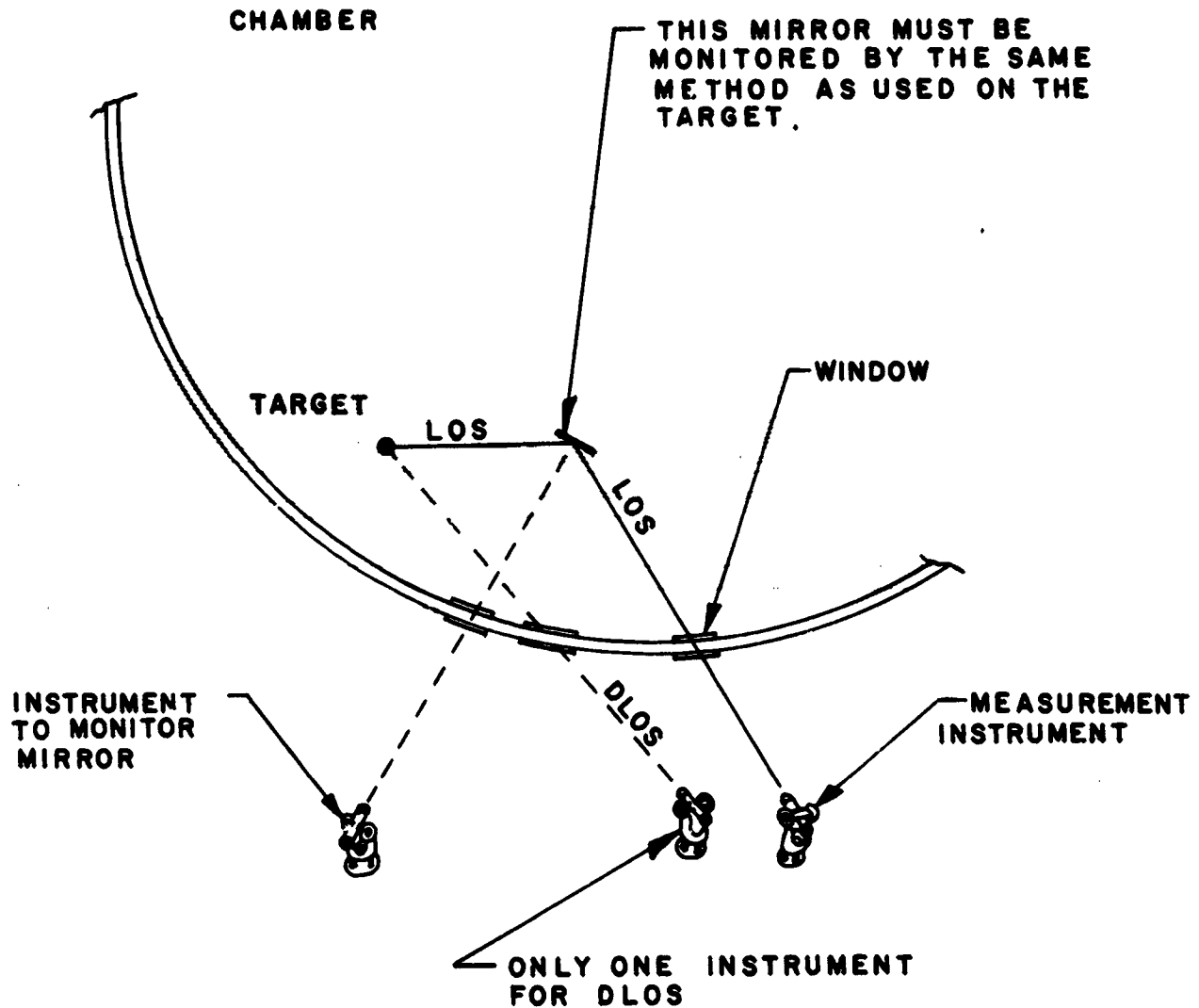flectors must be rigidly mounted.

CONCLUSION

Table one shows the various types of instruments and their respective
applicability for various types of measurements, test articles, and test
environments. In each case, the minimum number of instruments or laser beams
necessary to make the measurement is stated. Greater redundancy can, in
general, increase the accuracy of any particular measurement. This may be
achieved by increasing the number of instruments, provided each is aligned
along an additional line of sight or optical path. Additional cameras will
also increase the photogrammetric accuracy with the same proviso.

TABLE I

APPLICABILITY CHANNELS OF THE MEASUREMENT METHODS WITH THEIR RESPECTIVE INSTRUMENTATION CONFIGURATIONS FOR VARIOUS TEST SITUATIONS

CHAMBER

THIS MIRROR MUST BE
MONITORED BY THE SAME
METHOD AS USED ON THE
TARGET.

WINDOW

TARGET

LOS

LOS

DLOS

INSTRUMENT
TO MONITOR
MIRROR

MEASUREMENT
INSTRUMENT

ONLY ONE INSTRUMENT
FOR DLOS

THE DLOS ELIMINATES EXTRA MONITORING, AND
SHOULD BE USED UNLESS GEOMETRY PROHIBITS.

FIG. I   DLOS CONCEPT

TARGETED TEST
ARTICLE

THERMAL
VACUUM
CHAMBER

GAUGE
BAR

ANALOG
OUTPUT

THEODOLITE
STATION

THEODOLITE
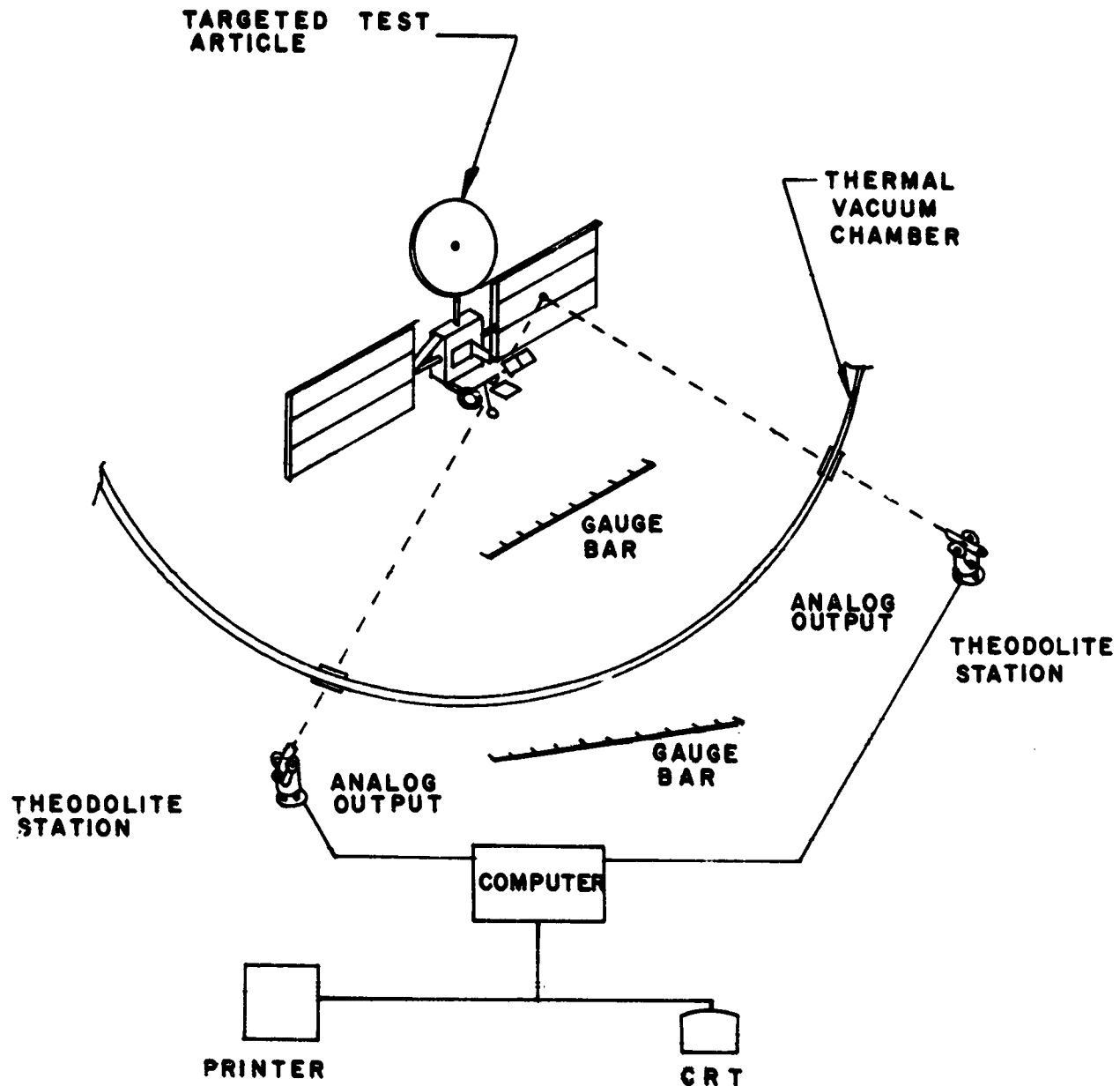STATION

ANALOG
OUTPUT

GAUGE
BAR

COMPUTER

PRINTER

CRT

FIG. 2

TYPICAL STEREOTRIANGULATION SETUP WITH THEODOLITES.
COMPUTER SHOWN FOR DIGITAL ELECTRONIC THEODOLITES.
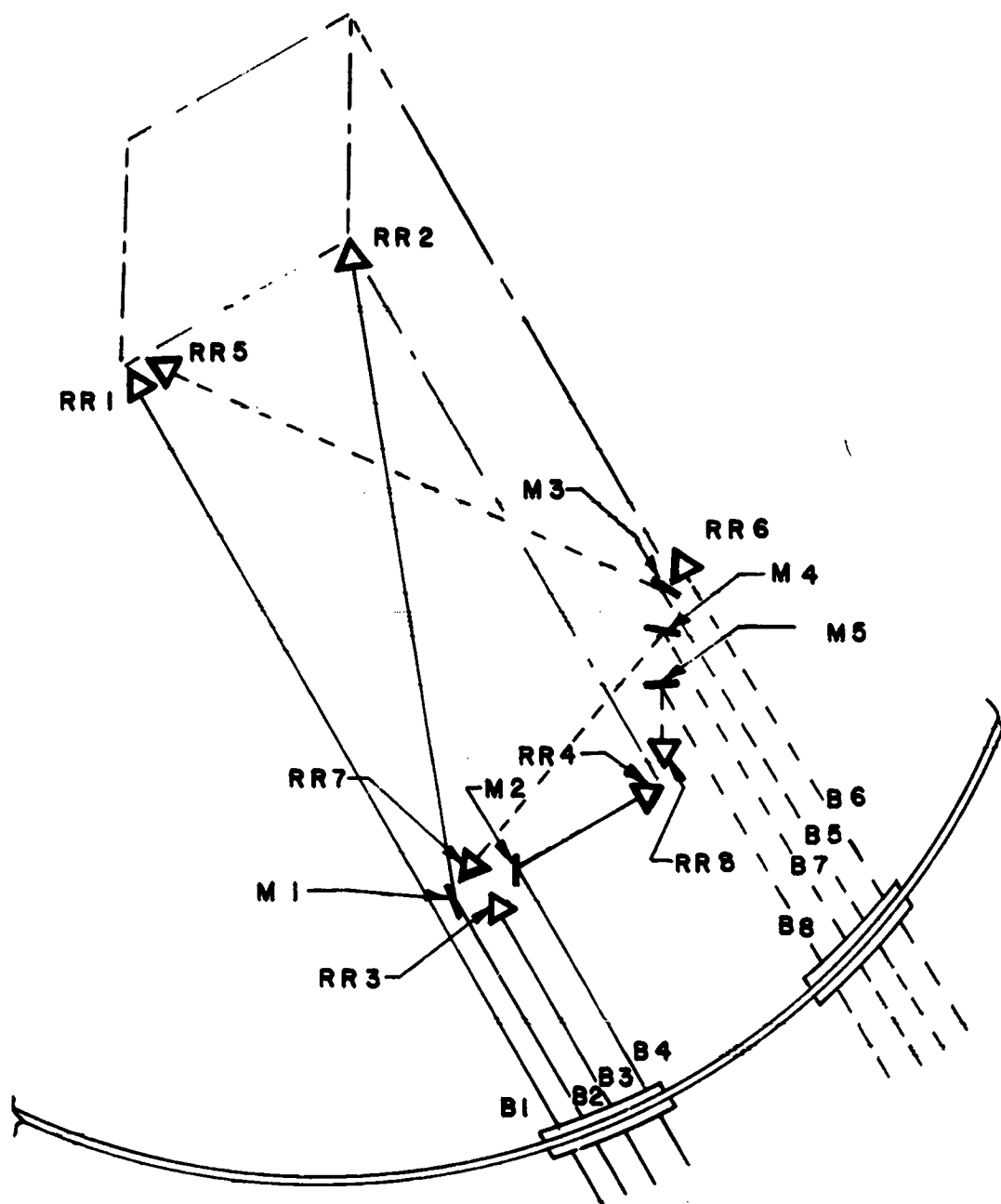GAUGE BAR MAY BE PLACED EITHER INSIDE OR OUTSIDE
OF CHAMBER.

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FIG. 3 TYPICAL SETUP FOR LASER INTERFEROMETRIC MENSURATION
OF ONE FACE OF A RECTANGULAR PARALLELAPIPED .
MINIMUM INSTRUMENTATION IS 4 SEPARATE INTERFEROMETER
BEAMS, (B1-B4), 4 RETROREFLECTORS, (RR1-RR4) AND
TWO MIRRORS (M1,M2). THIS SETUP MENSURATES MOTION
IN THE PLANE OF THE FACE ONLY. FOR MOTION
PERPENDICULAR TO THE FACE, ADDITIONAL BEAMS B5-B8
WITH THEIR RESPECTIVE MIRRORS AND RETROREFLECTORS
ARE NEEDED. THESE BEAMS ALSO MENSURATE THE LOWER
"END" FACE OF THE ARTICLE.