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US Army Research Laboratory

Transonic Experimental Facility (TEF) Free-Flight Spark Range: Automation of Film Reading and Processing

by Sophia M Haire

NOTICES

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Weapons and Materials Research Directorate, ARL

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14. ABSTRACT

Timely digitization of data points from projectile shadowgraphs collected from the free-flight spark ranges at the Aerodynamic and Transonic Experimental Facilities (AEF and TEF) at the US Army Research Laboratory (ARL) at Aberdeen Proving Ground, Maryland, have historically posed a challenge for ARL engineers and computer scientists. Manual processes involving the use of light tables to digitally log data points by directly reading the developed film negatives have been the standard approach. For AEF film reading, the process has only recently begun to be automated via in-house beta-version software. This software (the “film package”) consists of 3 Visual Basic.NET programs (FilmScanner, FilmSorter, and FilmReader), which are used sequentially to scan, order, and extract measurements from the shadowgraphs. Each component of the film package was modified and expanded to accommodate the film format and calculations required by TEF shadowgraphs. These modifications primarily consist of methods to process TEF film’s unique size and reference points, enhancements to image processing and quality, and introduction of modern hardware. Although there are several items to complete before ARL’s advent of fully automatic spark-range film analysis, the package is ready for use in digital analysis of TEF tests, and the efficiency gained by the film package warrants its use in present and future range operations.

15. SUBJECT TERMS

TEF, digital image processing

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- Mr Ron Anderson, for painstakingly testing the film package at various stages of completion.

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Student Biography

Sophia M Haire is a rising college sophomore studying computer science and mathematics at the University of Maryland, Baltimore County (UMBC) in Catonsville, Maryland. She is grateful to the US Army Research Laboratory (ARL) for the opportunity to digitize range operations as an ARL summer 2014 intern student. Her career and academic goals are to combine the technical/digital world with research of the human brain, memory, and the onset of dementia and related diseases that affect the elderly.

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1. Background

The Aerodynamic and Transonic Experimental Facilities (AEF and TEF) at the US Army Research Laboratory (ARL) are invaluable resources to the Army's research and development of small and large projectiles. Film data has been collected and analyzed from these facilities since the 1940s and is still heavily used in the analysis of projectiles to which onboard sensory electronic devices cannot be attached.[1]

Each of these facilities is similar to a long dark room, along which several numbered and timed camera stations are spaced to take flash pictures—or shadowgraphs—of projectiles during their flight paths. Two orthogonal shadowgraphs of each projectile are collected at each camera station and are used together to calculate key position data about the projectile's flight path.[2] Figure 1 is an example of a shadowgraph taken at the TEF range. Each shadowgraph displays 2 projectile images, 1 of the actual projectile and 1 of its shadow, which is the image used in measuring and processing. The reference bead and wire have known locations in space and are used to define a coordinate system via which the projectile's spatial location can be calculated. Each station number is followed by a character (for TEF film, either P or W), which denotes the location of the camera at the station that took that particular picture.

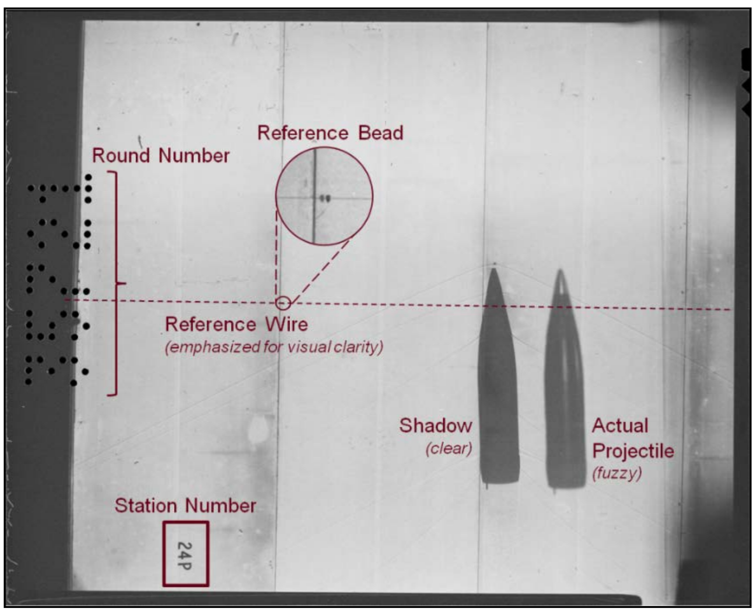

Fig. 1 TEF range shadowgraph with annotation

The reliability and efficiency of the processing of the shadowgraph data collected in these ranges is of high priority to the Lethality Division at ARL, but unfortunately, the methods used to process the data have not always aligned with that priority. Until recently, processing of both AEF and TEF shadowgraphs was accomplished manually with the use of archaic and cumbersome machinery. In 2011, a movement towards digitization of shadowgraph processing originated with the introduction of an in-house software suite for AEF film processing known as the film package. However, format and calculation differences between AEF and TEF shadowgraphs have heretofore prevented the modification of this capability for TEF film processing. This project represents the advent of the current foundational digital capability for TEF range film.

2. Film Package Overview

The film package is comprised of 3 Visual Basic.NET Windows forms applications—FilmScanner, FilmSorter, and FilmReader—which are run sequentially to scan, order, and extract measurements from shadowgraphs. The first 2 programs accomplish the digitization of the films themselves, and the final program allows for digital measurement extraction, processing, and analysis of calculated data (i.e., spatial position of the projectile's center of gravity, and pitch, yaw, and roll angles). Each of these programs required significant modification and enhancements both to the interfaces and the back-end procedures to accommodate TEF film, as well as additional documentation to clarify existing code.

2.1 FilmScanner

The first program, FilmScanner, allows the user to digitize shadowgraph film via a simple interface and modern scanning hardware. The program is comprised of event handlers that are linked to controls on the program's main form (Fig. 2). Those pertaining to input variables store parameters for the film (the round number of the projectile, the output folder into which the image will be saved, the desired file format of the scanned image, and the range at which the projectile was launched) and for the scanning hardware (the type of scanner to be used, the number of films to be loaded into the scanner at once, and, optionally, the total number of films to be scanned). These values are stored globally and used by output handlers to communicate with the appropriate scanner, allocate an appropriately sized buffer for the scanning area, and save that buffer into a file of the correct file format.

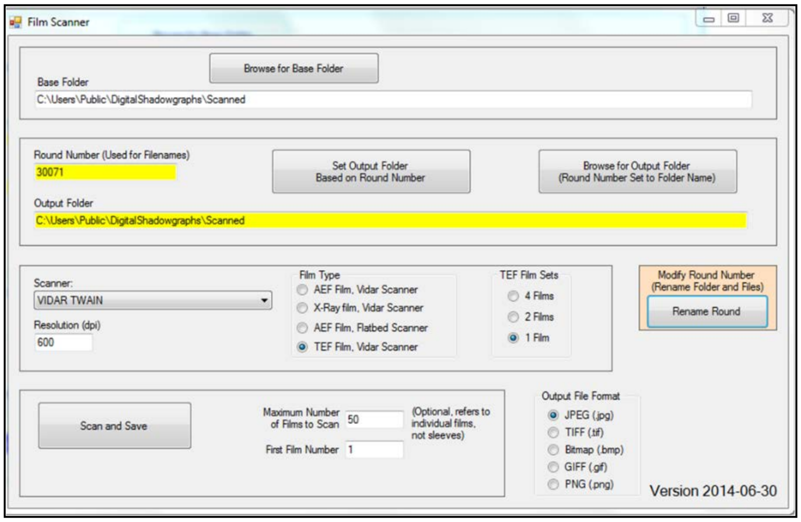

Fig. 2 Main form, FilmScanner

Each of the scanned images are then saved in an output folder where they are named sequentially (i.e., the first scanned JPEG image from round 12345 is 12345-001.jpg, the next will be 12345-002.jpg, and so on). FilmScanner uses functions from the Victor Image Processing Library[3] to interface with either of Vidar's DiagnosticPro Edge or DiagnosticPro Advantage scanner models via a Twain scanner driver and store individual TEF images in 4 inch × 5 inch (height × width) buffers that can be saved in 1 of 5 file formats (8-bit JPEG, Bitmap, GIFF, or PNG, or 16-bit TIFF). Modifications made for TEF film included the ability to interface with the DiagnosticPro Edge, allocation of the correctly sized image buffer for that scanner, and a means to scan multiple images into 1 buffer, segment the buffer, and save the segmented images individually when using the DiagnosticPro Advantage.

2.2 FilmSorter

FilmSorter serves as a preprocessing tool to associate scanned shadowgraphs with the camera stations at which they were taken and the camera location at that station used for that shadowgraph. Like FilmScanner, it uses input event handlers to store identifying data about the film to be sorted. It uses this data to generate a list of the station numbers with which a particular shadowgraph image can be associated and applies a new, sorted naming convention to the selected set of raw scanned images.

The FilmSorter code and interface encompass 3 primary image functionalities: display, enhancement, and sorting and storage. The former 2 sets of routines are implemented using functions from the Victor Image Processing Library, which allocate and modify image buffers, and Windows forms viewing controls, which display the contents of those buffers. Sorting and storage is accomplished through button-clicks on the second tab of the main form (Fig. 3). The form automatically generates a list of station numbers that correspond to the range at which the film was taken; that list is then displayed as several columns of button controls on the form. To associate an image with its station/location, the user clicks the appropriate button, and the program copies the image to the selected output folder with a filename that includes that station number and camera position (e.g., 12345_1-1_P.jpg refers to the image from round 12345 taken at station 1-1 by the pit position camera).

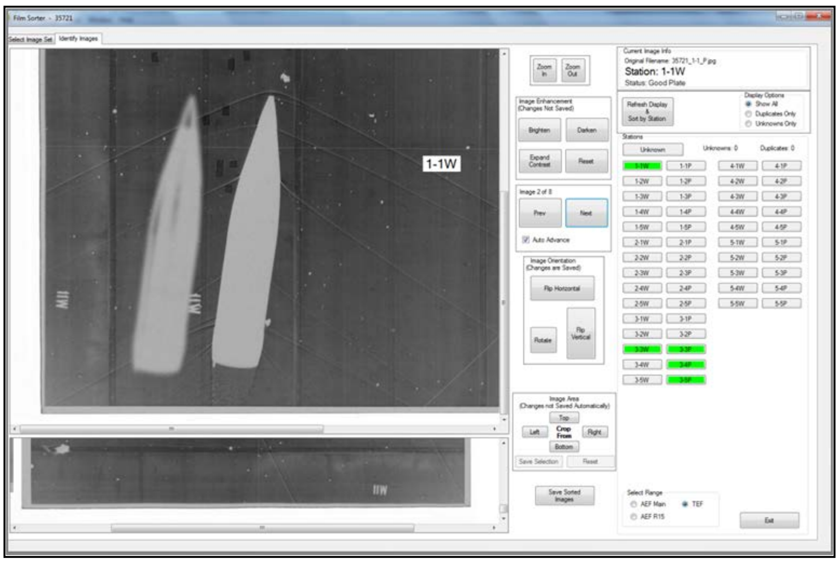

Fig. 3 "Identify Images" tab, main form, FilmSorter

The results of all the associations and other information about the film (range type, previous file name, and the quality of the physical film) are stored in a status file to be accessed later by FilmReader. Image-enhancement options of brightness/contrast adjustment, orientation changes, and cropping are included to aid in the visual component of making associations. The primary modifications made for TEF film were rotating the orientation of the secondary display window at the bottom of the form so that the station number could be viewed legibly and adding the cropping tool to trim the edges off of films that were scanned simultaneously and had a tendency to be saved with bordering whitespace in FilmScanner.

2.3 FilmReader

FilmReader allows the user to measure data points of interest from a set of sorted shadowgraphs and combine those measurements with the physical properties of the projectile to calculate the position of the projectile's center of gravity and its pitch, yaw, and roll angles over time. FilmReader's interface is divided into 5 tabs that are used to open a folder of sorted images, select the particular images to be measured, measure points of key locations on the projectile images via a point-and-click interface, process the results of these measurements, and display the resulting calculated data. The interface and event handlers of the first 2 tabs ("Open" and "Select") are similar to those of FilmSorter, and take the same input parameters to define a subset of the sorted images to be measured and processed.

2.3.1 Measuring

The measurements tab's functionality (Fig. 4) is implemented by 2 modules, ModuleCommon.vb, which handles the interpretation and storage of measured data, and ModuleImageProcessing.vb, which implements the point-and-click measuring interface. Both modules make use of a data structure associated with an image that stores measured points on the projectile, the enhancements made to the image, and flags indicating whether or not the image is ready for processing.

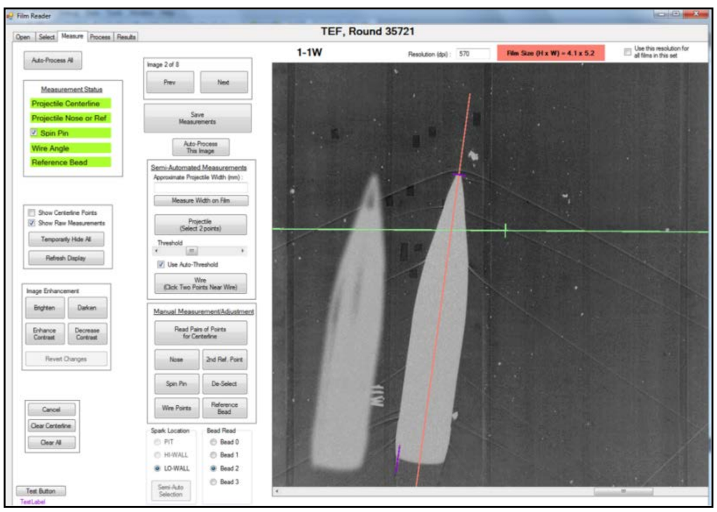

Fig. 4 "Measure" tab, main form, FilmReader

To measure a data point on a sorted image, the user first clicks on a button corresponding to the type of data point to be measured. For TEF shadowgraphs, data point types are the nose of the shadow projectile or another reference point, 2–4 points on the shadow projectile to define its centerline, 2 points on the reference wire, the center of 1 of the reference beads, and, if applicable, the center of the shadow projectile's spin pin. The button's event handler then sends a data string to a routine in ModuleCommon.vb, which interprets the string to prepare a storage location for the point to be selected. The user then follows a prompt on the bottom of the form to click on the selected item's location on the image, which is stored in the image's data structure and written to a data file whose contents are used in processing. The image can be zoomed in and out and enhanced to aid in selecting the correct point. This point is also passed to routines in ModuleImageProcessing.vb, which uses the point's 2-dimensional Cartesian values to mark its location on the image. Additionally, ModuleImageProcessing.vb allows the markings to persist when the display box is zoomed in or out, when a new image is measured and a previous one is returned to, or when a previously measured round is returned to after closing and re-opening the program.

For TEF film, 2 other quantities must be identified that do not correspond to data points on the film itself: the flash spark used when the image was taken and the number of the reference bead that was used. These are set and stored using sets of radio buttons near the bottom of the form. Their values for an image are usually defaulted to an appropriate value for the image's camera station number and stored automatically.

To enhance user-friendliness, FilmReader's "Measure" tab includes display options such as brightness/contrast adjustment functions that are implemented using functions from the Emgu OpenCV library.[4] The program also includes options for the user to measure the locations of the centerline and reference wire "semiautomatically"; in other words, the program uses the pixel intensity patterns of the image to fit points chosen near the wire or centerline to the actual locations of these features on the image.

TEF modifications required new interface options and data structure elements to accommodate the unique TEF reference points and values not associated with a raw point, a semiautomatic option for the reference wire, a semiautomatic option for determining the camera's spark location, and the image-enhancement capabilities.

2.3.2 Processing

Processing of measured points in FilmReader is primarily run using data input functions from ModuleCommon.vb and data calculation algorithms from the module RED, which is based on a Fortran program of the same name that was used to process manually measured points under the old film reading and processing paradigm. Calculation of essential values from the film data points requires several sets of external data about the projectile that was fired, including the projectile's physical properties, the times at which the shadowgraphs of that projectile were taken, the atmospheric conditions of the range at the time of the shot, and the spatial locations of reference points for the projectile's location (i.e., the reference bead and wire) for each camera station. For TEF shadowgraphs, this external data comes from survey data files, Excel spreadsheets, range data (or .ARL) files, manual inputs, and/or older results files used in previous calculations. ModuleCommon.vb interfaces with input event handlers on the process tab to load these physical values from user-specified sources and perform appropriate unit conversions on these values.

Once all the required values have been loaded to the form (Fig. 5), the RED module converts the data points measured by the user from a coordinate system defined by the image's upper-left corner to one defined by the projectile's location on the image; in the case of TEF film, this coordinate system's origin is located at the projectile nose or other reference point and has a y-axis that runs up from the base of the projectile to its nose along its centerline. The converted data points and the physical values are then stored (for now, in an intermediate file known as a TEF DAT file) and read by a subroutine in RED that runs them through an algorithm (directly converted from the legacy RED Fortran IV program) to convert the reference point locations in projectile coordinates to projectile center of gravity locations in range coordinates.

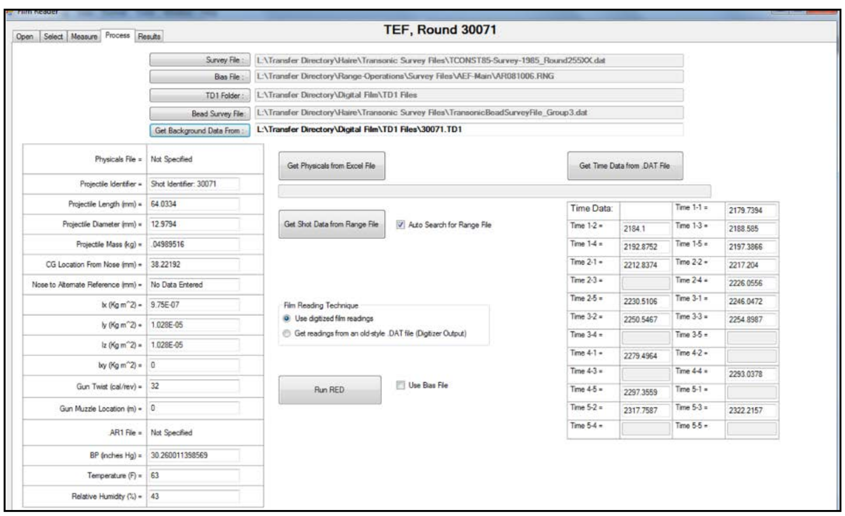

Fig. 5 "Process" tab, main form, FilmReader

These results, along with the roll angle of the projectile over time if a spin pin is present, are then stored in a final results file with extension .TD1 that can be read into FilmReader's "Results" tab so that a table of these values and scatterplots of the of the values with respect to the x-direction CG location, time, or station number can be analyzed for potential outliers. The .TD1 file is then used as input to a program called ARFDAS, where extensive analyses can be conducted.[5] Processing in FilmReader for TEF film required the creation of many new file Input/Output (I/O) capabilities, including reading from different types of spreadsheets, range data files, and survey files, accepting manual inputs, and creating the intermediate TEF DAT file behind the scenes. The center of gravity reduction algorithm in RED also had to be translated from the RED Fortran code and rewritten from the ground up in FilmReader.

3. Summary and Conclusions

The film package in its current stage of development is already providing an efficient alternative to the older, manual methods of TEF shadowgraph reading and processing. The suite has been tested by experienced personnel in the Flight Sciences Branch at ARL with previously processed shadowgraphs for rounds 30071 and 35933; and previously unprocessed shadowgraphs for rounds 39043 and 39313–39318. Cross-comparison of processed data has produced very promising results, with comparable residual error between the processed results produced by the manual methodology and those produced by FilmReader. For newer rounds with poor image quality, measurements taken in FilmReader appear to better describe projectile flight paths than those of measurements taken via the manual procedure. However, the film package still requires extensive user interaction, and, although error handling and established, documented processes in the code enforce reliability, this manual aspect is susceptible to human inconsistencies. As such, the film package is considered an intermediate enhancement of shadowgraph processing with a vision towards complete digitization and automation of the procedure. With this in view, the next goal for this procedure is for digital camera hardware to be installed on-range so that the digitization of the shadowgraphs can be done without human aid and for an automatic film reading capability to be added to FilmReader so that human intervention is minimized and maximum efficiency is achieved. This will require the disuse of both FilmScanner and FilmSorter. Nevertheless, the film package represents a significant milestone in the augmentation of the efficiency and reliability of ARL range operations.

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2. Braun WF. The free flight aerodynamics range. December 1987. BRL Report No.: 1048.

3. Victor Image Processing Library, Catenary Systems Inc., 2013. Web. Accessed 29 July 2014. http://www.catenary.com/.

4. Emgu CV, 2014. Web. Accessed 04 August 2014. http://www.emgu.com/.

5. Arrow Tech Associates. ARFDAS: Ballistic range data analysis system: user and technical manual. South Burlington, VT, May 1997.

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Appendix A. Film Package Code – Image Data Structure and RED CG Reduction

```
Public Structure tImage                              ' image information
structure
        Public Station As String
        Public Status As String
        Public Modified As Boolean
        Public HaveAllReadings As Boolean
        Public Active As Boolean
        Public Paired As Boolean
        Public FullFilename As String
        Public SeqNum As Integer     ' sequence number for display when not all
images selected
        Public CBj As Integer, CBk As Integer       ' indices of the associated
checkbox
        Public Resolution As Double                 ' resolution (dpi)
        Public xNose As Double, yNose As Double ' projectile nose  (all
measurements in pixels)
        Public xRef2 As Double, yRef2 As Double     ' alternate reference point
        Public xCenter1 As Double, yCenter1 As Double      ' point 1 of
projectile centerline
        Public xCenter2 As Double, yCenter2 As Double      ' point 2 of
projectile centerline
        Public xSpinPin As Double, ySpinPin As Double      ' location of spin
pin
        Public xFid As Double, yFid As Double              ' AEF: fiducial notch
        Public xFidLine1 As Double, yFidLine1 As Double    ' AEF: point 1 of
fiducial line
        Public xFidLine2 As Double, yFidLine2 As Double    ' AEF: point 1 of
fiducial line
        Public xBead As Double, yBead As Double            ' TEF: reference bead
location
        Public xWire1 As Double, yWire1 As Double   ' TEF: point 1 of wire
        Public xWire2 As Double, yWire2 As Double   ' TEF: point 2 of wire
        Public FilmType As Integer  ' TEF: second digit in 3-digit code: 0 =
PIT, 1 = HI-WALL, 2 = LO-WALL
        Public BeadRead As Integer  ' TEF: third digit in 3-digit code: Bead
used is 0-3, with bead locations 3 2 0 1 from left to right
        Public RefPtCode As Integer ' TEF: first digit in 3-digit code: 0 =
Nose, 1 = Alternate  Reference Point

        ' Image Enhancement Info
        Public BrightShift As Integer ' amount by which individual pixel
brightnesses have been shifted
        Public Contrast As Double     ' factor by which individual pixel values
have been multiplied

        ' Automatic Spark Selection Info
        Public ActualProjectileX As Double   ' x-location of a point on the fuzzy
projectile image
End Structure
```

tImage Data Structure Declaration in FilmReader. *This structure is declared in ModuleCommon.vb; comments are in green.*

```
'***** PIT Calculations *****
X1P = FA * NX1P
Z1P = FA * NZ1P
X2P = FA * NX2P
Z2P = FA * NZ2P
CXP = X2P - X1P
```

```
SZP = Z2P - Z1P

If CXP < 0 Then
       CXP = -CXP
       SZP = -SZP
End If

SRP = Math.Sqrt((CXP * CXP) + (SZP * SZP))  ' cvt_red_cg.for:
DXP = -((X1P * CXP) + (Z1P * SZP)) / SRP          '  DX = FVC * (D5 + D7) - D1
DZP = ((X1P * SZP) - (Z1P * CXP)) / SRP           '  DZ = FVC * (D6 + D8) - D2
DTP = SZP / CXP

' Determine appropriate reference point location via bead read
Call BeadOffset(NBP, NC1P, DXP, B1PIT, B2PIT, B1WALL, B2WALL, B3WALL)

'***** WALL Calculations *****
X1W = FA * NX1W
Z1W = FA * NZ1W
X2W = FA * NX2W
Z2W = FA * NZ2W
CXW = X2W - X1W
SZW = Z2W - Z1W

If CXW < 0 Then
       CXW = -CXW
       SZW = -SZW
End If

SRW = Math.Sqrt((CXW * CXW) + (SZW * SZW))
DXW = -((X1W * CXW) + (Z1W * SZW)) / SRW
DZW = ((X1W * SZW) - (Z1W * CXW)) / SRW
DTW = SZW / CXW

' Determine appropriate reference point location via bead read
Call BeadOffset(NBW, NC1W, DXW, B1PIT, B2PIT, B1WALL, B2WALL, B3WALL)

XH = SCH + (SCM * DXP)
ZH = SCM * DZP
YV = SCV + (SCN * DXW)
ZV = SCN * DZW

RX = SCA - (XH * SCB)                        ' used for calculations, defined in
BRL 900
RY = SCC - (YV * SCD)                        ' used for calculations, defined in
BRL 900
CH = RX + (ZH * SCB * DTP)                   ' used for calculations
CV = RY + (ZV * SCD * DTW)                   ' used for calculations

XR = (XH + (RX * YV)) / (1 - (RX * RY))' X coord. of ref. pt. (inches), defined
in BRL 900
YR = YV + (RY * XR)                      ' Y coord. of ref. pt. (inches), defined
in BRL 900
ZRH = ZH * (1 - (YR * SCB))              ' Z (horizontal) coord. of ref. pt.,
defined in BRL 900
ZRV = ZV * (1 - (XR * SCD))            ' Z (vertical) coordinate of ref. pt.,
defined in BRL 900
ZCH = FF * (ZRH - ZRV)                'Zcheck = difference of Z coordinates in
???
ZCH = ZCH / 0.003                     'Zcheck = diff. in mm??

If N2 = 1 Then
```

```
        ZR = ZRV ' Aero Range (use Z coordinate of direct image, not mirror)
Else
        ZR = ZRH ' Transonic Range (use horizontal, or pit, z coordinate) (why
not use average?)
End If
' (The preceding if statement was initially coded as: ZR=ZRV*FLOAT(2-
L2)+ZRH*FLOAT(L2-1)  where L2=N2)

RMP = (DTP + (CH * DTW)) / (1 - (CH * CV))  ' ratio of m/p, defined in BRL 900
RNP = DTW + (CV * RMP)                          ' ratio of n/p, defined in
BRL 900
DCP = 1 / Math.Sqrt(1 + (RMP * RMP) + (RNP * RNP))  ' direction cosine p
DCM = RMP * DCP                                         ' direction cosine m
DCN = RNP * DCP                                             ' direction
cosine n
X = FF * (XR + (D11 * DCM) + SCX)    ' X CG location in range coordinates and
meters
Y = FF * (YR + (D11 * DCN) + SCY)    ' Y CG location in range coordinates and
meters
Z = FF * (ZR + (D11 * DCP) + SCZ)    ' Z CG location in range coordinates and
meters
```

RED Center of Gravity Reduction Algorithm in FilmReader. This algorithm, a direct conversion of the RED FORTRAN code, is implemented in the subroutine Convert_CGTEF in module RED.vb.

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