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Langley 16-Ft. Transonic Tunnel Pressure Sensitive Paint System

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Abstract

This report describes the NASA Langley 16-Ft. Transonic Tunnel Pressure Sensitive Paint (PSP) System and presents results of a test conducted June 22-23, 2000 in the tunnel to validate the PSP system. The PSP system provides global surface pressure measurements on wind tunnel models. The system was developed and installed by PSP Team personnel of the Instrumentation Systems Development Branch and the Advanced Measurement and Diagnostics Branch. A discussion of the results of the validation test follows a description of the system and a description of the test.

Introduction

The Langley 16-Ft. Transonic Tunnel, shown in figures 1 and 2, has been used since 1950 to test various military aircraft and NASA spacecraft at transonic speeds.¹ It is an atmospheric, closed-circuit tunnel with a slotted test section operating at Mach numbers of 0.2 to 1.25. This report describes a system recently installed in this facility that uses pressure sensitive paint (PSP) to provide global surface pressure measurements on wind tunnel models tested in the facility.

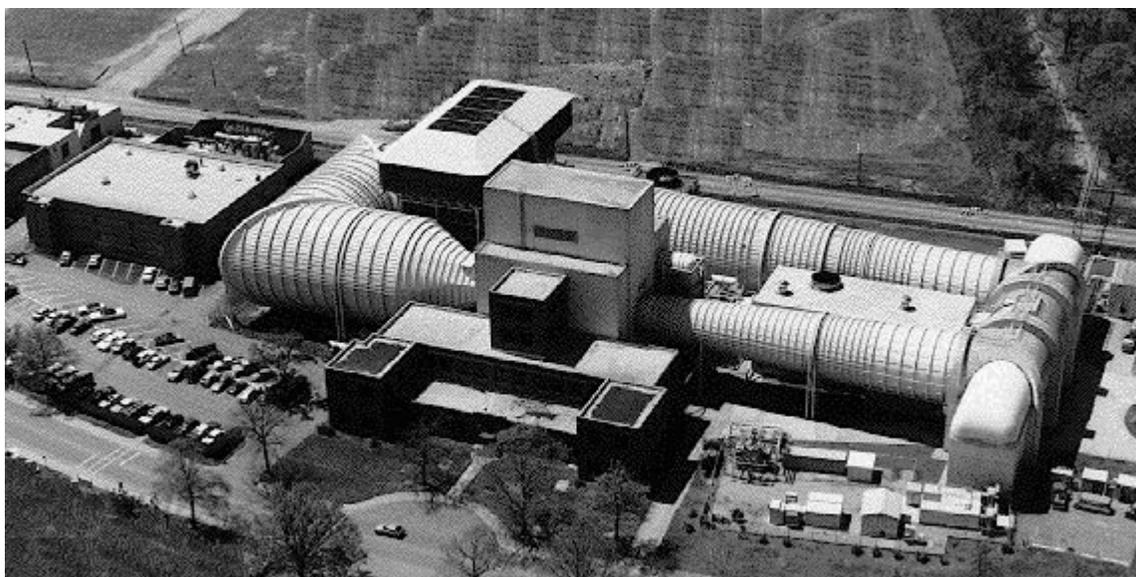


Figure 1. NASA Langley 16-Ft. Transonic Tunnel .

¹ F. J. Capone; L. S. Bangert; S. C. Asbury; C. T. Mills; and E. A. Bare: *The NASA Langley 16-Foot Transonic Tunnel---Historical Overview, Facility Description, Calibration, Flow Characteristics, Test Capabilities*. NASA TP-3521, 1995.

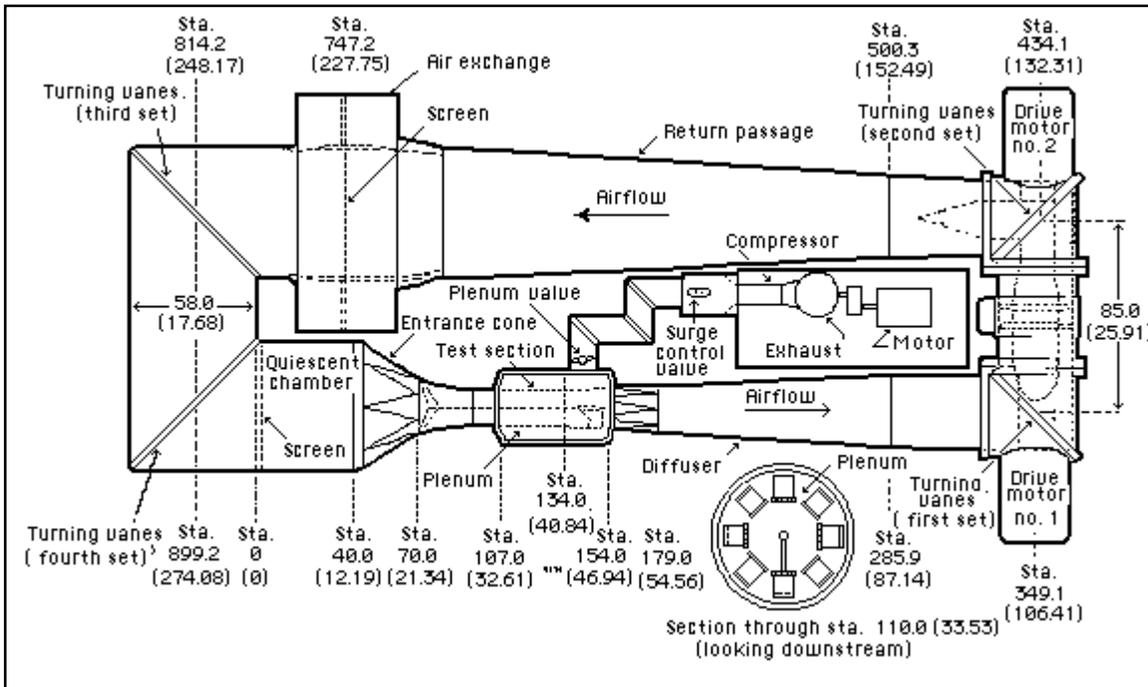


Figure 2. Tunnel diagram. Dimensions are in feet (meters).

When exposed to light of an appropriate wavelength, pressure sensitive paint luminesces with an intensity inversely proportional to the partial pressure of oxygen of a given environment. When applied to a wind tunnel model it can be used to provide a picture of the varying pressures over the model surface. An image is acquired with tunnel wind off, another image is acquired with wind on, and these images are ratioed and calibrated against model surface static pressure tap data to render C_p in the form of a false-color image. PSP has been used at Langley in various wind tunnels including 16-Ft. TT since the early 1990's.² With the demonstrated success of this useful measurement technique it was determined that a dedicated PSP system would be a desirable component of the 16-Ft. TT complement of test techniques. It was thus in 1999 and 2000 that PSP Team personnel of the Instrumentation Systems Development Branch (ISDB) and the Advanced Measurement and Diagnostics Branch (AMDB), at the request of the Research Facilities Branch (RFB), designed and installed in this facility a PSP system to provide global surface pressure measurements on wind tunnel models. A test to validate the PSP system was conducted June 22-23, 2000, the results of which are discussed following a description of the system and a description of the test.

PSP System Requirements

The system was designed by PSP Team personnel to fulfill the following requirements:

The system should be able to operate over an expected lifespan of five years. Future upgrades will extend the useful life of the system. Daily operation should be limited to 3 hours of continuous use. With controlled use, the system can be used daily over a two-shift operation. A

² T. R. Amer.; C. Obara.; W. Goodman; B. Sealey; C. Burkett; and T. Carmine: Pressure Sensitive Paint Measurements in NASA-Langley Wind Tunnels. *Proceedings of the 45th International Instrumentation Symposium*, Instrument Society of America, 1999, pp. 325-334.

set of standard operating procedures (SOP) will be provided by the PSP Team. The requirements for each system component are as follows:

Paint Chemistries

- Capable of operating over the entire operating range of the tunnel (pressure, temperature, and speed)
- Capable of operating for one week per paint application

Paint Application

- Capable of being applied in the test section
- Maintain proper safety procedures as defined by the SOP
- Meets SOP for thickness and roughness
- Must be able to prepare, apply, and cure within 8 hours (includes basecoat and PSP)
- Clean-up in accordance with SOP

Lighting

- Average total output of $250 \mu\text{W}/\text{cm}^2$, not to exceed $1000 \mu\text{W}/\text{cm}^2$
- Filtered to output between 360 and 400 nm
- Use existing window ports
- Withstand 180°F environment (light source only)
- Power supplies to be installed external to plenum
- Remote on/off located in control room
- LED status indicator for each light located in control room

Image Acquisition

- Capable of running one or two cameras using existing ceiling window
- Camera to be protected from dirt and oil. Air cooling to be provided for camera body
- Above enclosure to include facility safety camera
- Liquid cooling unit and electronic control unit to be installed outside plenum
- Camera tilt, pan, f-stop, and focus to be manually adjusted
- Field of view coverage for a typical model, approximately 6 ft by 6 ft maximum
- Filtered to receive between 630 and 670 nm
- Remote on/off capability located in control room
- Triggering provided by tunnel data system or image acquisition computers
- Data images provided in TIFF 6 format (for image processing)
- Data back-up provided by CD-R writer

Image Processing

- Must be able to accept tunnel data system outputs for pressure tap data, test parameters (run and point number) and test conditions in real time
- Processed data (image ratios) available within one hour of completed run

Maintenance

- Maintenance of the system hardware to be performed by the specific manufacturers or in-house maintenance personnel/contracts
- Software maintenance to be provided by ISDB
- Upgrades to the system hardware and/or software to be made available as necessary (including but not limited to floor and side wall installations for full model coverage)

- System support available from ISDB

Schedule

- Lab checkout of system to be completed by end of June 1999
- Installation to be completed by the end of August 1999
- Training (paint application and image acquisition/processing) to be completed by end of September 1999
- System validation test to occur in FY00

Training

- Training for paint application will be provided
- Training for image acquisition and processing will be provided

Documentation

- Will be turned over to facility for configuration control
- Manufacturer manuals
- Test requirements and plan
- Standard Operating Procedures
- Mechanical and electrical drawings

System Description

Paint Application System

The Paint Application System is owned and maintained by ISDB and consists of paint guns, air supply pump, air hoses, chemical solvents, curing lamps, protective gear, and other associated hardware as shown in figure 3. The paint used for the Validation Test was a Langley-developed 2-step paint prepared by personnel in AMDB. It consists of a primer and a PSP that are applied and cured separately (see Discussion of Results below).



Figure 3. Paint Application System.

Lighting and Image Acquisition System

A diagram of the Lighting and Image Acquisition systems is shown in figure 4. The system consists of 12 excitation lamps and two scientific grade digital cameras mounted inside the plenum with the support electronics for the lamps and cameras located outside the tunnel to protect them from the temperature extremes associated with the operation of the tunnel. The support electronics for the cameras and lights are housed in two electronics cabinets mounted on top of the tunnel with a common feed-through connector plate located between the cabinets. Two data acquisition computers and a control box are located inside the control room. Approximately 150 feet of cable is routed between the control room and the electronics on top of the tunnel. All cabling is required to pass through the plenum area of the tunnel to the upper/lower disconnect point so that the cables may be easily disconnected for the raising of the upper part of the tunnel to allow for model changes.

Lighting is provided by twelve 250-watt ultraviolet inspection lamps outfitted with manufacturer supplied band pass filters centered at 365 nanometers. The power for each lamp is independently selectable from the tunnel control room using a custom fabricated solid state relay power distribution system. Installed into each lamp is an output monitor detector with the signal from each providing a Light Emitting Diode (LED) indication in the tunnel control room when each lamp's output is 80% of rated output or higher. Custom designed and fabricated mounting brackets were used to mount the lamps to existing optical ports on the side wall of the tunnel. The 9-foot long manufacturer-supplied cables between the lamp power supplies and respective

lamp heads were replaced with cable lengths up to 40 feet including bulkhead feed-through connectors to allow for the placement of the lamp power supplies outside of the harsh temperatures in the tunnel.

Image acquisition was accomplished using two scientific grade 16-bit digital charge-coupled device cameras. The cameras each have 512 x 512 pixel sensor arrays that are liquid-cooled. The cameras are each outfitted with optical band pass filters centered at 650 nanometers in addition to an infrared blocking filter. A sheet metal housing was designed and fabricated to protect the two cameras from the temperature extremes of the tunnel as well as to keep the cameras free from oil and dirt that accumulates in the top of the plenum area where the cameras are mounted. The housing is lined with foil backed foam board insulation to reduce the amount of heat transferred into the camera housing. The camera housing is cooled by a vortex cooler using house-supplied compressed air. Camera temperatures were monitored using two thermocouples inside the housing with the temperature readout located in the control room. The cameras were mounted inside the housing using slotted aluminum extrusion rail material. The rail system that was designed and fabricated is insensitive to tunnel vibration while allowing for pan and tilt adjustments of each camera independently.

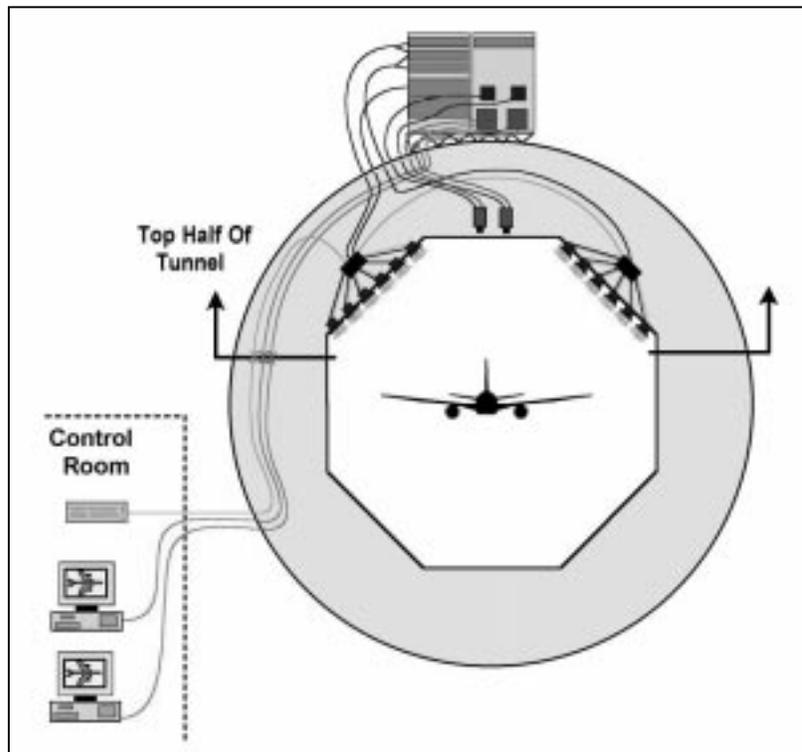


Figure 4. System installation in the tunnel.

Image Processing System

The Image Processing System uses Greenboot™ software that was developed jointly by McDonnell Douglas, NASA Ames, and Sterling Software. GreenBoot™ is designed to operate under UNIX operating systems. The system uses an SGI-O2 with operating system version 6.5 and Greenboot™ version 2.12a.

GreenBoot™ uses database methods that allow access to image files, tunnel data, configuration set-up, and geometry data of the model. GreenBoot™ accommodates macros to automate image processing. These macros are presented in the appendix.

PSP data reduction converts intensity data in the image plane to pressure data mapped to spatial coordinates of the model plane. This a multi-step process that includes the following steps:

- Image correction
- Image registration and ratioing
- Calibration to pressure data
- Correction for mapping
- Conversion to Cp,
- Transformation from 2-D image plane to 3-D model plane

Validation Test

After installation of the PSP system a test was conducted to validate all parts of the system including paint application, 12 lights, 2 cameras, cabling, optical lenses & filters, image acquisition & processing software, tunnel data communications, and remote monitoring & activation capabilities.

Test Requirements

1. Prepare, prime, paint, cure, and register 6-foot wingspan model with FEM at 1.7-2.7 mil thickness and 10 microinches or better roughness in 8 hours or less inside the test section.
2. Verify all 12 lights are working and model surface is illuminated at an average of 250 and not exceeding 1000 microwatts per cubic centimeter.
3. Verify light activation from control room.
4. Verify function of 12 LED light indicators in control room.
5. Verify 6' by 6' field of view.
6. Verify both cameras capable of acquiring focused images with pixel counts of 62,000 (16-bit mode).
7. Demonstrate dark and flatfield corrections.
8. Demonstrate multiple images can be acquired when triggered by tunnel data system.
9. Verify SGI can acquire tunnel data system outputs for pressure tap data, test parameters and test conditions in real time.
10. Demonstrate ratioed images available within one hour after acquisition.
11. Demonstrate image acquisition over range of Mach 0.2 to 1.25 and AOA from -10 to +20 degrees.

Test Personnel:

ISDB:

Clifford Obara—PSP Team Leader, image acquisition

Danny Sprinkle—PSP Test Engineer, image acquisition & processing

Tahani Amer—Lead Image Processor

Cecil Burkett—PSP Technician, image acquisition & processing

Michael Carmine—PSP Technician, model painting, image acquisition
 Bradley Sealey—PSP Technician, system design & installation

AMDB:

Bradley Leighty—PSP Technician, system design & installation
 Dr. Donald Oglesby—PSP Chemist, paint consultant

RFB:

Darlene Pokora—Tunnel Test Engineer
 Wes Goodman—Image Processor

Tunnel Technicians:

Jeff Bullock—Model Painter
 Bryan Pierce—Model Painter

Model

The model used to validate the PSP System was an F-18 with a 40-inch wingspan that was scheduled for six weeks of testing (Test 537). The first two days of this six weeks were provided solely for the validation test.

Test Plan and Results

Table 1 shows the test plan and gives the results.

Table 1. Test Plan

Operation	Date and Time Verified	Comments
Model prepped	AM 6-19-00	
Model primed	AM 6-19-00	
Model painted	AM 6-20-00	
Model cured	AM 6-20-00	
Model registered	AM 6-20-00	
Registration measurement	AM 6-21-00	
All 12 lamps working and controllable from control room	PM 6-20-00	
Light level at model surface averages 250 $\mu\text{W}/\text{cm}^2$		Took measurements 6-20-00 afternoon. Average level: 100 $\mu\text{W}/\text{cm}^2$. Highest level: 130 $\mu\text{W}/\text{cm}^2$.
Light level at model surface less than 1000 $\mu\text{W}/\text{cm}^2$		See above.
12 LED lamp indicators in control room operative	PM 6-20-00	
Each camera can see 6' by 6'	AM 6-20-00	
Each camera adjusted to render focused images with pixel counts of 62,000 maximum (16 bit)	AM 6-20-00	Cameras were adjusted to render about 40,000 counts maximum. This was done to prevent saturation.
Acquire dark and flatfield images	AM 6-19-00	Performed flatfield, 36 per F-stop
Appropriate camera filters installed	PM 6-20-00	

Multiple images acquired by both cameras when triggered	6-22-00	Multiple trigger function was used for dark images.
Test parameters supplied from tunnel in real time		This was not demonstrated during the Validation Test. RFB personnel plan to implement this.
Test parameters received and recorded by SGI in real time		Test parameters are recorded by tunnel data system and transferred to SGI after test.
Ratioed images viewable within 1 hour of image acquisition		This was not demonstrated during the Validation Test, but during the ensuing F-18 Test.
Images acquired over Mach 0.2 to 1.25 and AOA -10 to +20 degrees	6-22-00	Mach .2 to .9; AOA -6 to +18

Test Matrix

PSP images with wind on were acquired at angles-of-attack of -4, 0, 7, and 15 degrees. In addition, wind-off images were acquired after each wind-on run with of -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 5, 6, 7, 8, 9, 13, 14, 15, 16, 17, and 18 degrees. Wind-on runs were at 0.2, 0.6, and 0.9 Mach. The test matrix for the Validation Test (Test 537 Runs 5-36) is given in table 2.

Table 2. Test Matrix

Run #	Test Points	Mach #
5	216-219	0.2
6	224-243	0
7	248-251	0.6
9	256-280	0
11	300-312	0
12	317-320	0.6
13	325-344	0
14	349-352	0.9
15	357-376	0
17	381-384	0.2
18	389-408	0
19	414-417	0.9
20	422-441	0
21	446-449	0.2
22	454-473	0
23	478-481	0.2
24	486-505	0
25	508-511	0.9
26	517-536	0
27	541-544	0.6
28	549-569	0
29	574-577	0.2
30	582-601	0
31	607-610	0.6

32	615-634	0
33	642-645	0.2
34	650-669	0
35	674-677	0.9
36	688-702	0

Discussion of Results

Paint Application

The model preparation, painting, and curing process was carried out in the test section. This took place over two days and thus did not meet the specified system requirements for a 1-shift time limit. For the validation test a 2-step process was used where a coat of primer and a coat of PSP are applied separately.

In the 2-step process the model is cleaned with solvent and masked in preparation for painting. The model is first painted with the primer and is cured for several hours using heat lamps. After cooling, the primer is treated with solvent before applying the PSP. The PSP is applied and cured with heat lamps. After cooling, the PSP-plus-primer is measured for thickness and roughness. An ink marker is then used to apply registration marks that are required for processing the images acquired during the test. Lastly, the locations of these registration marks are measured in relation to the model by use of a coordinate measuring machine. This is also required for image processing.

In a test subsequent to the validation test, a 1-step application was tested where the PSP and primer were mixed and applied to the model together and allowed to dry without heat curing. This greatly expedited the painting process and brought the required time to within one shift (8 hours). Results from this test validated the 1-step paint application process.

Although the validation test lasted only two days, it was shown in subsequent testing that one paint application could be used for more than one week of 2-shift-per-day testing. Due to constraints imposed by model limitations, angles-of-attack were kept within -4 to $+15$ degrees and wind speed was never over Mach 0.9. Therefore, the originally specified validation test requirements of -10 to $+20$ degrees and Mach 0.2 to 1.25 were not demonstrated.

Lighting and Image Acquisition

An average total output of 100 microwatts-per-cubic-centimeter was measured at the model surface with the highest measured level of 130 microwatts-per-cubic-centimeter. This was considerably less than the specified 250 microwatts-per-cubic-centimeter, but this still achieved a two-thirds camera response with less than one second exposure times. The lighting system was demonstrated to withstand temperatures typically encountered during summer.

Both cameras were triggered by the tunnel data system. All images were saved in TIFF-6 format. All image files on hard drive were routinely backed up on CD-ROM by inboard CD-R writers. More than 300 images were acquired in the validation test. (Since the validation test, more than 15,000 images have been acquired.)

Image Processing

Image files to be processed were transferred to the dedicated SGI after each run as needed. All test parameters and pressure tap data were also transferred from the tunnel data system after each run. Processing data in the form of ratioed images less than one hour after a run was demonstrated. Each image processed required about 15 minutes to render C_p data. This time can be reduced by automating the image processing software. Processed images are not included in this report because this information is restricted.

Training

Two tunnel technicians (Jeff Bullock and Bryan Pierce) were thoroughly trained in the painting process prior to testing. For the validation test, however, ISDB personnel painted the model. The same technicians were trained on the image acquisition system during and after the validation test. Two RFB engineers (Wes Goodman and Darlene Pokora) were trained to process images on the SGI using Greenboot™ software.

Future Action

Among the possible actions considered to maintain, supplement and/or enhance the existing system are:

1. Install an alarm system to monitor camera temperatures.
2. Purchase a third camera for backup.
3. Purchase lamp components for backup.
4. Conduct periodic checks of lamps to ensure proper function.
5. Automate image acquisition system to accept both trigger and tunnel parameters from tunnel data system.

Summary

The Langley 16-Foot Transonic Tunnel Pressure Sensitive Paint System has been fully validated. It is comprised of a 2-camera image acquisition system, an SGI based image processing system, and the means and know-how to apply PSP to test models and acquire and process the images to render global model surface pressures. The PSP Team stands ready to consult with RFB 16-Ft. TT staff in order to maintain their state-of-the-art PSP System.

Appendix

Image Processing Macros

mgb0

```
./mgb1 352 9367 353 9383 352 9349
```

mgb1

```
# Open a wind off image and process up to the point where targets
# are to be selected.
# three sets of parameters are required
# if no dark image, use "" "" as place holders
# these parameters will carry into m2 ( the follow on macro )
# $1 --> dark run number
# $2 --> dark point number
# $3 --> off run number
# $4 --> off point number
# $5 --> on run number
# $6 --> on point number
#
# for m2
set dark_run=$1
set dark_point=$2
set m2_run=$5
set m2_point=$6

# open image *.tif
# rename and save as *.off
# subtract the dark image
# threshold the off image
# exit, leaving image displayed for targeting
#
# find a wind off image that matches the run and sequence number
DEF_IMAGE WOF -type=off -run=$3 -seq=$4 -ext=TIF
if ($status) then
  echo "No wind off image found for run $3 and sequence $4"
  exit
endif

# protect the original image by renaming and saving it
RENAME_IMAGE $WOF $4 -extension=off
SAVE_IMAGE $WOF

#release the wind off tif image
FREE_IMAGE $WOF

#now find the off image
DEF_IMAGE WOF -type=off -run=$3 -seq=$4 -ext=off
if ($status) then
  echo "Could not reload the off image!"
  exit
endif
```

```

if ($dark_run) then
# find a dark image that matches the run and sequence number
DEF_IMAGE DARK -type=dark -run=$dark_run -sequence=$dark_point
if ($status) then
  echo "No dark image found for run $dark_run and sequence $dark_point"
  exit
endif

```

```

# subtract the dark image from the wind-off image
SUBTRACT $WOF $DARK -adjust
endif

```

```

#threshold the off image
THRESHOLD $WOF -background

```

```

#done as much as we can - now let the operator take over
DISPLAY_IMAGE $WOF

```

```

echo "Set targets then run m2"
exit

```

mgb2

```

#
# the is stage 2 of a 2 part macro script
#
# stage 1, m1, loaded the wind off, subtracted the dark image and
# presented the off image for target information
#
# variables that should be left from m1 include
# WOF --> wind off image *.off
# DARK --> dark image
# m2_run --> on run number
# m2_point --> on point number
# start off by saving the off image
SAVE_IMAGE $WOF

# get a wind on image using m1 variables
DEF_IMAGE WON -type=on -run=$m2_run -seq=$m2_point -ext=TIF
if ($status) then
  echo "Unable to locate a wind on image for run $m2_run and sequence $m2_point"
  exit
endif

```

```

# save the image as *.on
RENAME_IMAGE $WON $m2_point -extension=on
SAVE_IMAGE $WON

```

```

# show the operator what is going on
DISPLAY_IMAGE $WON

```

```

#
# the is stage 3 of a 6 stage macro script
#

```

```

# free on *.tif image and reobtain as *.on
FREE_IMAGE $WON

DEF_IMAGE WON -type=on -run=$m2_run -seq=$m2_point -ext=on
if ($status) then
  echo "Unable to reload saved on image (on)"
  exit
endif

if ($dark_run) then
  # subtract the dark image from the wind on image then release the dark image
  SUBTRACT $WON $DARK -adjust
  FREE_IMAGE $DARK
endif

THRESHOLD $WON -background

SAVE_IMAGE $WON

# copy the target from the off image to the on image
#COPY_TARGETS $WON $WOF -xradius=2 -yradius=2 -tolerance=0.04
DISPLAY_IMAGE $WON

# stage 4 of 6
# save the current image as a warp
SAVE_IMAGE $WON -extension=wp

# register is used vice correlate due to dropping
# targets by correlate

CORRELATE $WON -reference=$WOF -poly2 -selectall

# stage 5 of 6

#ratio the wind on image

DIV_INTO $WON $WOF

# no longer need the wind off image
COPY_TARGETS $WON $WOF -xradius=2 -yradius=2 -tolerance=0.05
FREE_IMAGE $WOF

MODEL_POSITION $WON -3d -selectall

# stage 6 of 6

# calibrate the tap data to exposed image
Tap_calibrate $WON -fit_2 -3x3 -oblique=50

# rename as pressure image and save
RENAME_IMAGE $WON $WON -extension=cp

SAVE_IMAGE $WON

# free this image space

```

```
FREE_IMAGE $WON
# and retrieve as pressure (shows in title of image)
DEF_IMAGE WON -type=on -run=$m2_run -seq=$m2_point -ext=cp
DISPLAY_IMAGE $WON

# generate the plot image
Tap_calibrate $WON -fit_1 -3x3 -oblique=50 -plot_image
```

mgb3

```
#
# Map to Grid

MAP_TO_GRID $WON $WON".cfl" -Outward -Oblique=70

OPEN_WINDOW -Geometry

DISPLAY_IMAGE $WON".cfl"
Set_legend $WON -Max_value= 0.5 -Min_value=-1.8 -Increment= 0.2
```

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13. ABSTRACT (Maximum 200 words) This report describes the NASA Langley 16-Ft. Transonic Tunnel Pressure Sensitive Paint (PSP) System and presents results of a test conducted June 22-23, 2000 in the tunnel to validate the PSP system. The PSP system provides global surface pressure measurements on wind tunnel models. The system was developed and installed by PSP Team personnel of the Instrumentation Systems Development Branch and the Advanced Measurement and Diagnostics Branch. A discussion of the results of the validation test follows a description of the system and a description of the test.				
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