Temporal Processing of Millimeter Wave Flight Test Data

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ABSTRACT

This paper describes work that was done to improve millimeter-wave radar image by utilizing temporal processing on radar data collected during a recent flight test program on the NASA AIRES aircraft.

These flight tests were part of the Follow-On Radar, Enhanced and Synthetic Vision Integrated Technology Evaluation (FORESITE) project under the NASA Aviation Safety and Security Program (AvSSP) Synthetic Vision Systems (SVS) program.

Analog radar IF signals were digitized and the digital data output was recorded during the flight tests. The digital data was replayed after the flight tests and a number of samples were post processed using a temporal processing algorithm with the intention of evaluating this temporal algorithm and assessing the computational requirement. The images enhanced by temporal processing exhibit a significant improvement in image quality.

1.0 INTRODUCTION

A flight test program was conducted during August and September of 2005 on the NASA ARIES test aircraft, a Boeing 757-200 (Figure 1) based at NASA's Langley Research Center. The flight test area concentrated on the Wallops Island airfield off the northeast Virginia coast. Eight evaluation flights were made, including two night flights, in addition to seven demonstration flights (including one practice demo flight) for a total of 15 flights. The system under test fused imagery from a 94 GHz imaging radar with the output from two Infrared cameras and displayed the resulting image on a Head Up Display (HUD). During tests, a number of low level approaches were performed where an obstacle (a truck) was deliberately placed at the end of the runway to determine whether the pilot would spot the return from the object in the fused radar/IR image on the HUD, with the objective of providing an intuitive visual incursion warning capability. During the test program, the raw radar data was recorded for future analysis and the evaluation of new processing techniques, including temporal processing.

Figure 1. BAE Systems 94 GHz Radar Systems Flight Test – the NASA 757-200

2.0 TEST SYSTEM DESCRIPTION

Figure 2 is a simplified representation of the system architecture. The 94-GHz imaging radar was mounted in the nose radome. The Infrared sensors were mounted in a fairing on the underside of the aircraft. Output signals from the Infrared sensors were processed though a computer and sent to the Enhanced Synthetic Image Processor (ESIP). The ESIP provided radar processing which produced a C Scope millimeter wave image. The millimeter wave image and an infrared sensor images were then fused, mapped, and warped together in the Image Processor Module located inside the ESIP and sent to the Head Up Display (HUD) in the cockpit for presentation to the pilot. The ESIP communicates with an External Control Computer via bi-directional RS-422 communication links.

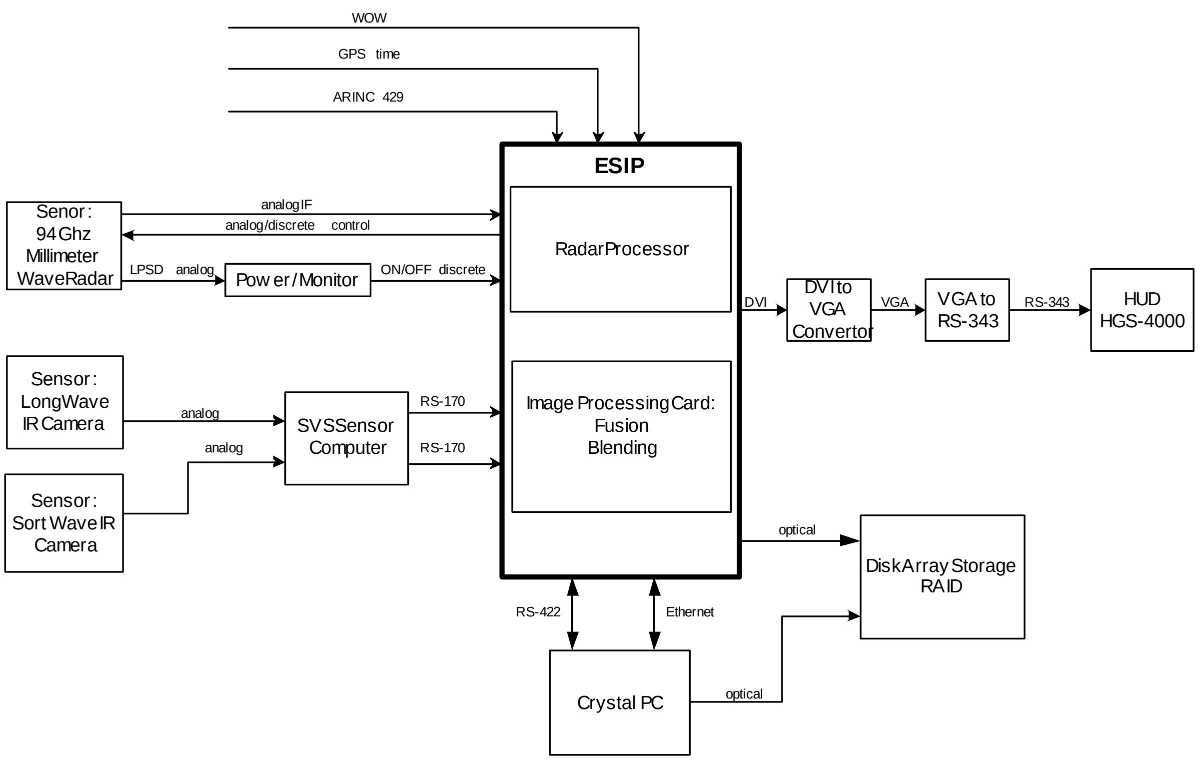

Figure 2. Enhanced Vision System of NASA Aries B-757 Architecture

Real time image processing was performed within the ESIP to provide imagery for the HUD. An example of the 94 GHz radar, real time image produced without temporal processing, is shown in Figure 3. The Radar's analog (base band) IF signals were digitized and recorded on a Disk Array during the flight for the post flight temporal processing investigation.

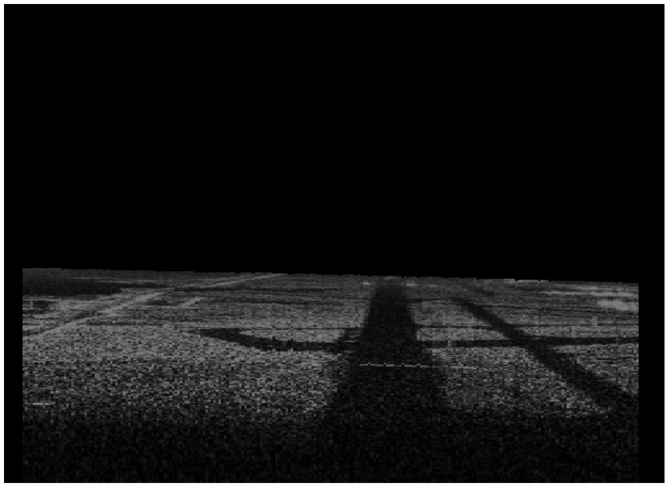

Figure 3. 94 GHz radar real time runway image without temporal processing during the flight test – August 2005

3.0 THE TEMPORAL PROCESSING OF FLIGHT TEST DATA

3.1 Coordinate Definition

Consider the forward looking radar installed in the aircraft nose, as shown in Figure 4.

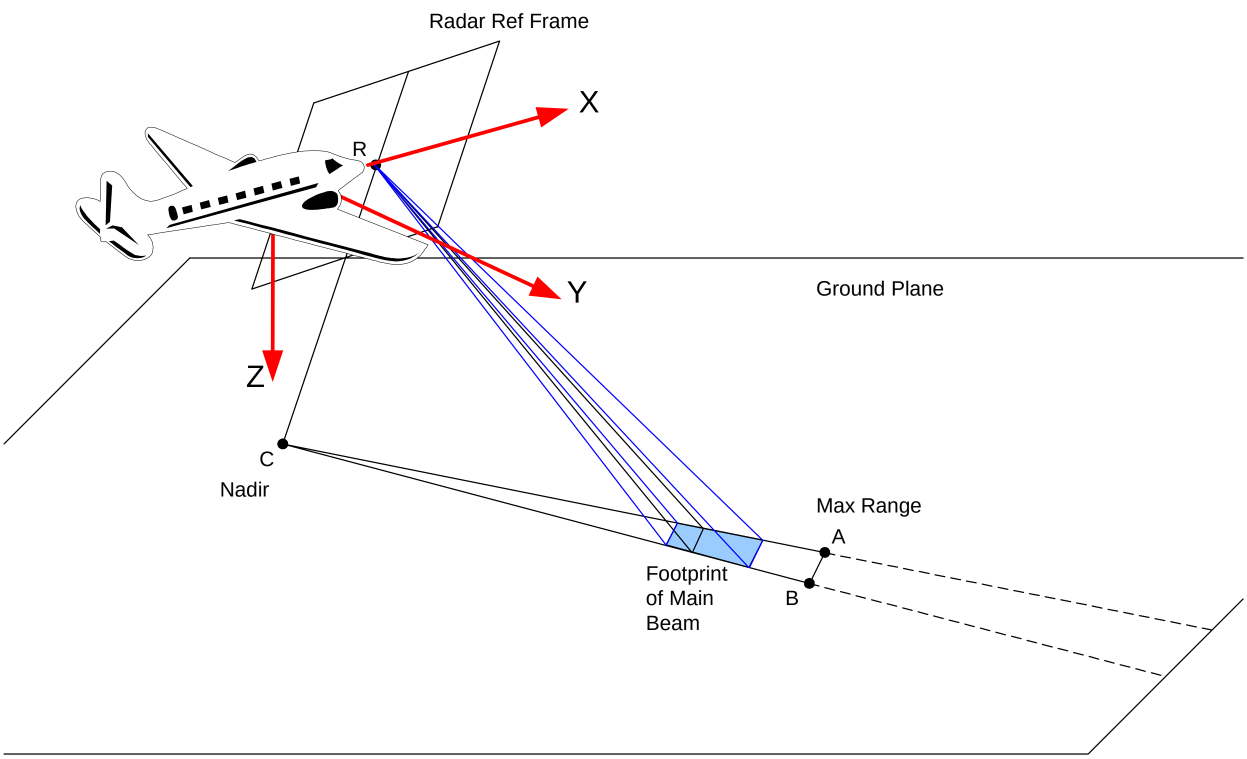

Figure 4. Imaging scene of millimeter wave radar

The coordinate systems are defined as follows.

a. (A) World Earth Centered, Earth Fixed (ECEF) frame. XY plane is the Equator plane with X axis crossing Prime Meridian. Z axis points to North Pole.

b. Navigational North East Down (NED) frame. X axis points to North, Y axis points to East, and Z axis points down. Centered with the aircraft center of mass.

The Earth Centered, Earth Fixed (ECEF) frame and North East Down (NED) frame is shown at Figure 5.

c. Aircraft Body (Body) frame. X axis point forward out of the nose of the aircraft, Y axis points to the right (out of the right wing tip), and Z axis point down (out of the belly of the aircraft). Centered with the aircraft center of mass.

d. Local Level (Level) body frame. Coincidental with the aircraft body frame and Z axis aligned with the gravity vector.

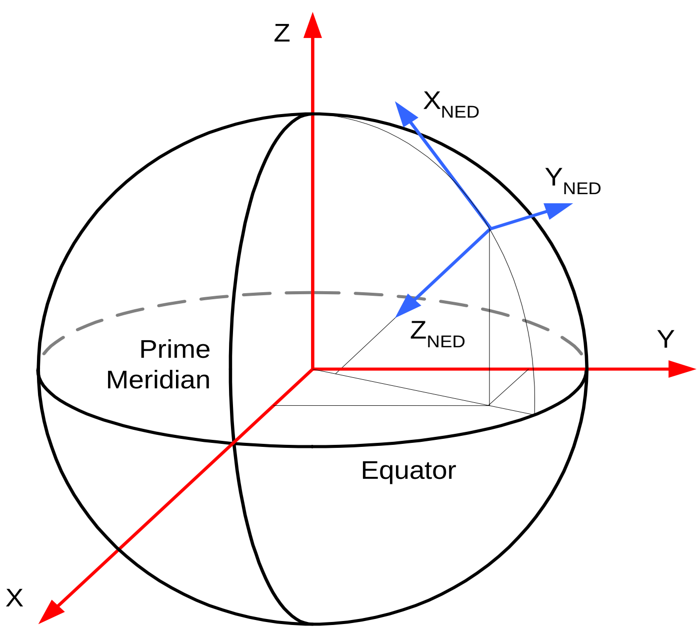

Figure 5. Earth Centered, Earth Fixed (ECEF) frame in red color and North East Down (NED) frame in blue color

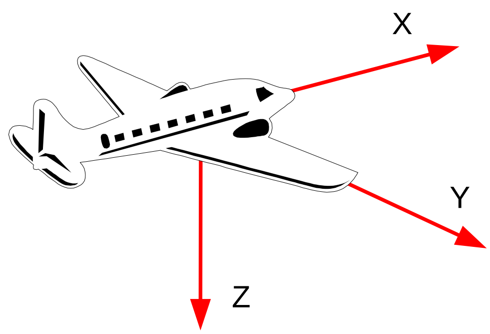

Figure 6. Aircraft Body Frame and Local Body Frame

e. Radar Installation (Radar) frame. Fixed with respect to the aircraft body frame with its origin at the radar servo swivel point. Relation between the aircraft body frame and radar installation frame is characterized by translation and rotation.

f. Radar Image (Image) frame. Coincidental with the radar installation frame when the radar antenna is pointing at zero degrees in elevation. This frame rotates with the antenna in elevation. The Y axis is identical to the radar installation frame. Mechanical azimuth rotations of the antenna are performed about Z axis of this frame.

3.2 Algorithm Description

3.2.1 Unit Vector Definition

Consider normal vector to the Local Level (and ground) plane $n^{Level} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$

Transform this normal vector of Local Level frame to the Radar Image frame:

$$n^{\mathrm{Im}age} = Transform\ Level\ frame\ to\ Radar\ Image\ frame\ (\, n^{Level}, p(pitch), r(roll), e(elevation)\,)$$

Define the Local Level frame origin as:

$$P^{Level}_{LevelOrg} = (0,0,0)$$

Transform the Local level frame origin point to a point in the Image frame

$$P^{\mathrm{Im}age}_{LevelOrg} = Transform\ Level\ to\ Image\ (\, P^{Level}_{LevelOrg}, p(pitch), r(roll), e(elevation)\,)$$

The normalized unit vector is written as:

$$\overline{n}^{\mathrm{Im}age} = Normalize(n^{\mathrm{Im}age} - P^{\mathrm{Im}age}_{LevelOrg})$$

3.2.2 Point to Point Distance

The distance from radar Image frame original to the point at ground plane is calculated as

$$d_{initial} = \frac{height}{\overline{n}^{\,Image} \bullet z_u}$$

Where $z_u = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$ is unit z vector in the Image frame. $\bullet$ - dot product operator.

The point P_n at Image frame is

$$P_n = \overline{n}^{\,Image} \cdot d_{initial}$$

Assume the radar scan at selected nine azimuth angle, i.e. the azimuth values shift nine times, the shift value is account for the incremental computation from point one to point nine.

In order to calculate the distance from the point at Image frame to the point perpendicular to earth surface, let's define the vectors

$$r = \begin{bmatrix} \cos(azimuth_i + azshift) \\ \sin(azimuth_i + azshift) \\ 0 \end{bmatrix} \otimes \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

Where *azimuth*$_i$ *= initial azimuth angle. azshift = incremental azimuth angle*
$\otimes$ is a cross product operator.

And $q = Normalize(\overline{n}^{\,Image} \otimes r)$

The perpendicular distance from Image frame origin point to the point of earth surface is

$$d_{perpend} = \left| q \otimes P_n \right|$$

The distance from imaging point P_n to the point perpendicular to earth surface $P_{perpend}$

$$d_{pn\_perpend} = \sqrt{d_1^2 - d_{perpend}^2} \qquad \text{if } \left| d_1 - d_{perpend} \right| > \varepsilon \text{, where } \varepsilon = 0.0001$$

$$= 0 \qquad \text{otherwise}$$

The distance from the points $P_{perpend}$ and instantaneous maximum imaging point $P_{instant\,max.}$ is:

$$d_{perpend\_instant\,max} = \sqrt{INST.MaxRange^2 - d_{perpend}^2}$$

And distance between the initial image points P_n and instantaneous maximum imaging point $P_{ins\tan t\max}$ can be written as

$$d_{pn\_ins\tan t\max} = d_{pn\_perpend} + d_{perpend\_ins\tan t\max} \text{ (if the antenna depression angle is negative)}$$
$$= d_{pn\_perpend} - d_{perpend\_ins\tan t\max} \text{ (otherwise)}$$

The fundamental point to point relationship is shown at Figure 7 below.

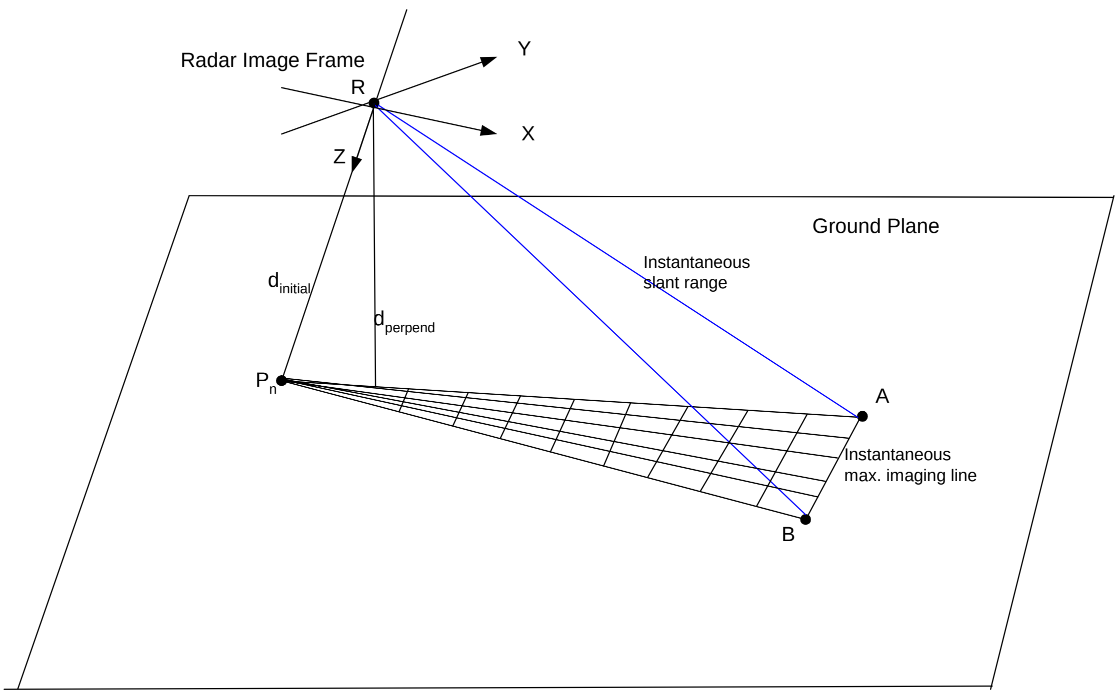

Figure 7. Point-to-Point Distance Relationship

3.2.3 Range Compensation and Texture (Image) Construction

If we walk the line from P_n to $P_{ins\tan t\max}$. step by step, the incremental step distance is defined as

$$\Delta d = \frac{d_{pn\_ins\tan t\max}}{Rangebin}$$

Where “Rangebin” is the number of range bins assumed at the processing stage.

Range compensation is performed at each $\frac{\Delta d}{2}$ point for display gain adjustment.

A compensation look up table is pre-established from an empirical result. The first compensation point is expressed as

$$P_{n\_1stcompensation} = P_n + (q \cdot \frac{\Delta d}{2})$$

Each range profile has its own gain value after range compensation at each point. It is written as

$$Rangeprofile_{i-1,0} = LookupRange(\left|P_{n\_1stcompensation}\right|, i-1)$$

Range profile gain value is interpolated between the values of the two neighboring profile bins if the

$$P_{n\_1stcompensation} / rangeresolution \quad \text{(is not an integer)}$$

Based at our azimuth scan angle, from – xy degrees to + xy degrees, we construct the N images which is equal to the ramp duration of transmitting wave. The formation of the ground patch for image rending is shown in Figure 8.

The return data in the imaging frame is transformed from image frame coordinates to the Local Level, NED and ECEF frames. Each ground patch layer represents one radar scan cycle.

During each rendering cycle, the pilot's current design eye position is used as the viewing position for rendering, and the orientation of the viewport is adjusted to match the aircraft attitude. The previously processed ground referenced textures are then rendered onto a ground plane positioned at the airfield altitude.

Multiple textures are available for each ground location and these are blended together during the rendering process to reduce the noise in the images presented to the pilot.

The rendering process is shown in Figure 9.

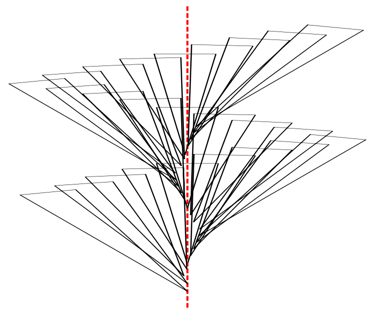

Figure 8. Ground patch construction for image rendering

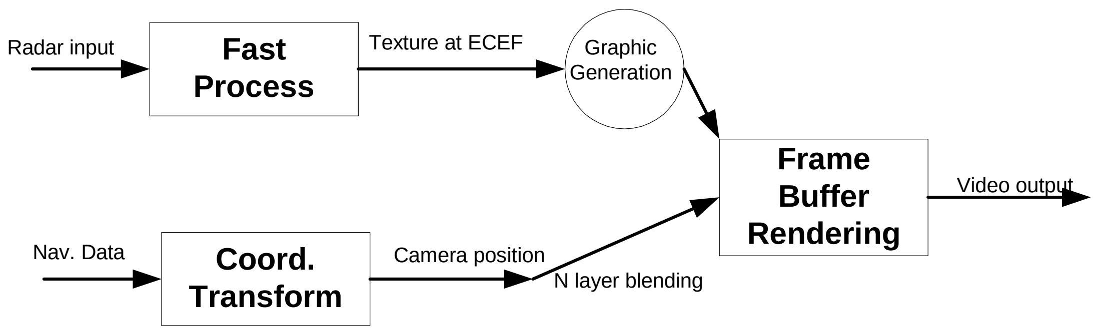

Figure 9. Video process of N layers image rendering

3.3 Processing Results

The flight test data was processed off line using the algorithm described above. The resulting images show that the temporal processing has reduced the image noise and improved the runway image. Figure 10A and Figure 10B show a comparison in performance between unprocessed and processed images for the same view of a runway from an approaching aircraft.

Figure 10A. Unprocessed Radar Image

Figure 10B. Temporally Processed Radar Image

Figure 11 through Figure 15 are a series of pictures which show the images generated as the aircraft overflies the runway, and are displayed as C-scope projections and a corresponding bird's-eye view image

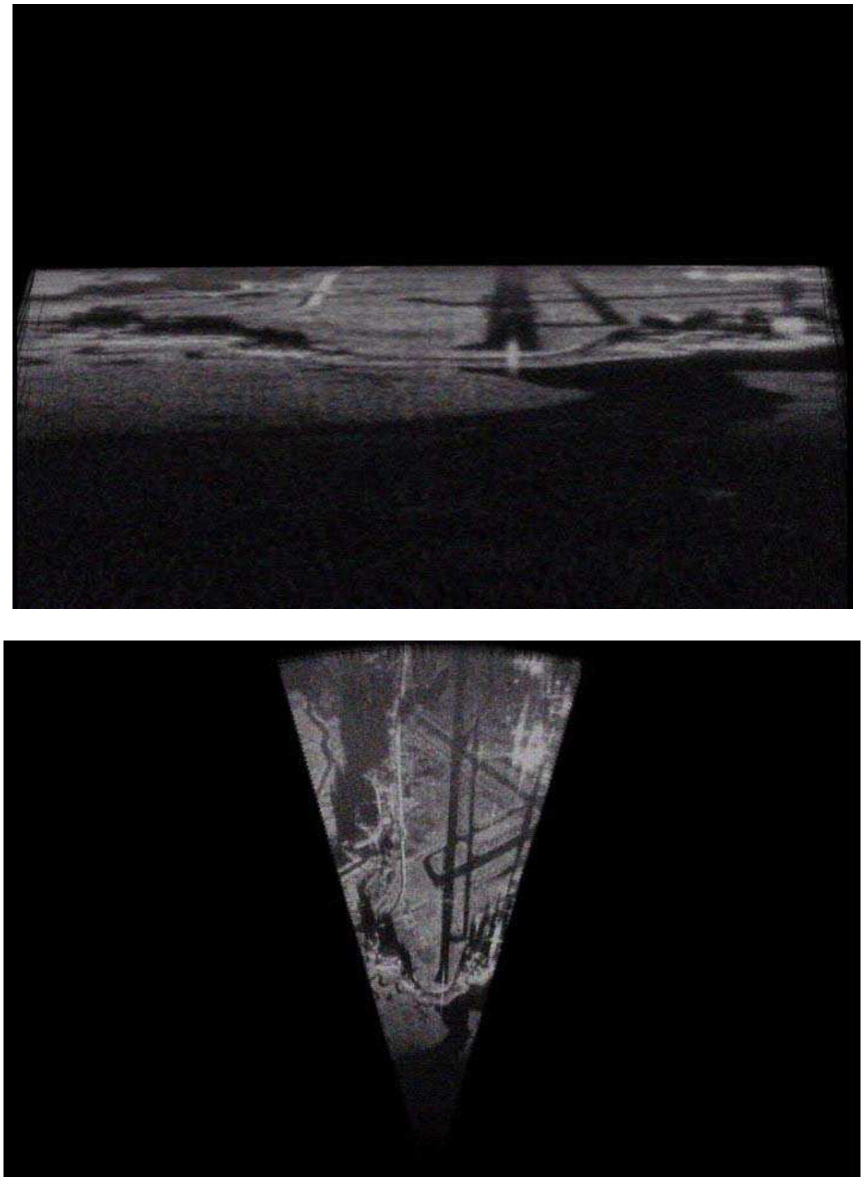

Figure 11. Runway image on approach after temporal processing

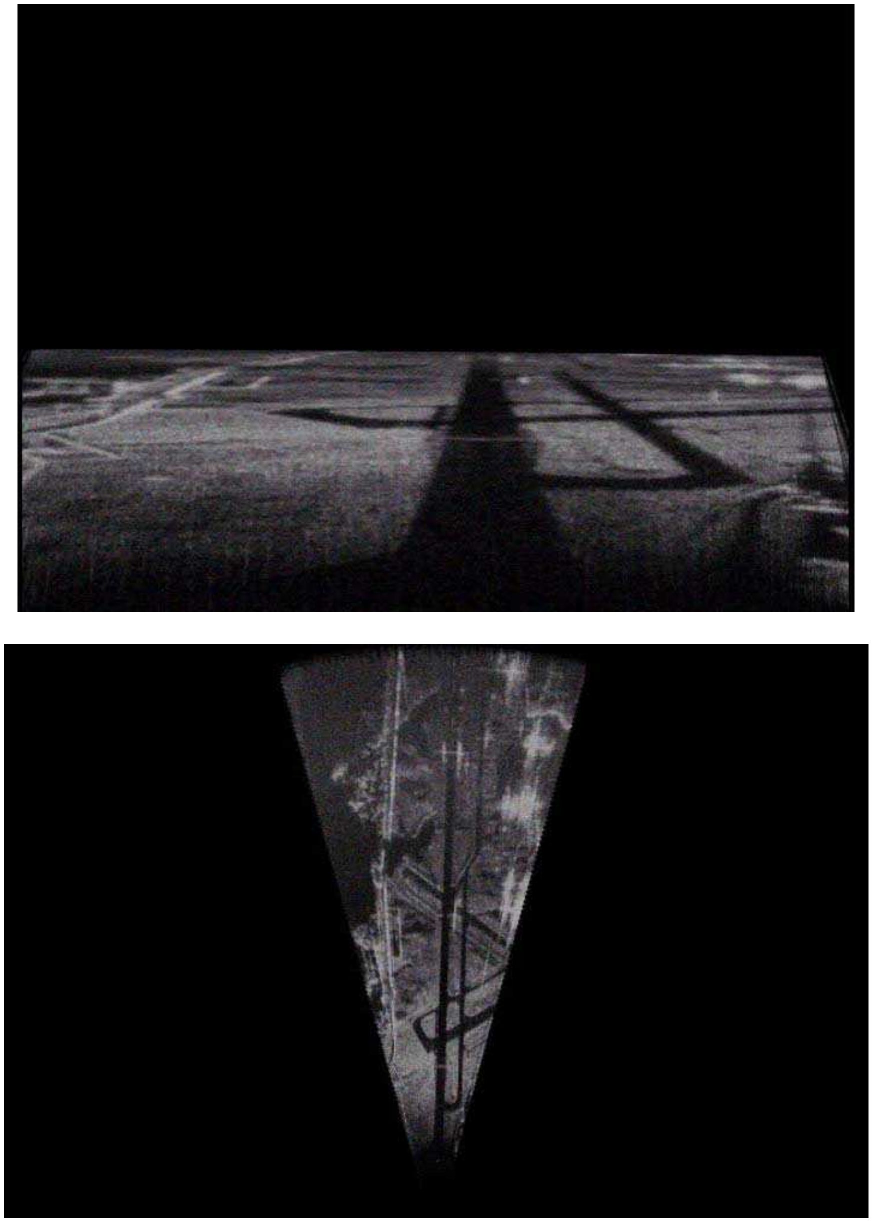

Figure 12. Runway image on approach after temporal processing

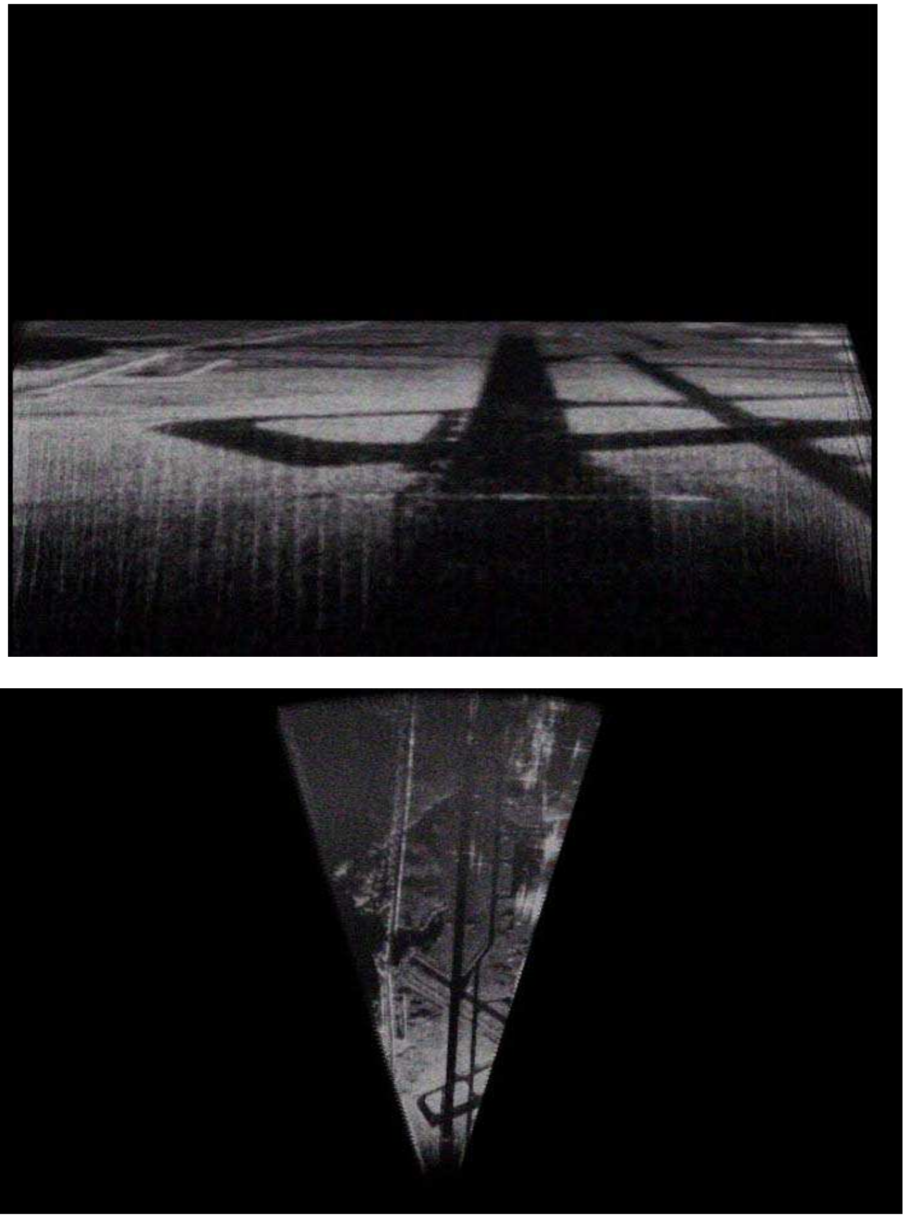

Figure 13. Runway image on approach after temporal processing

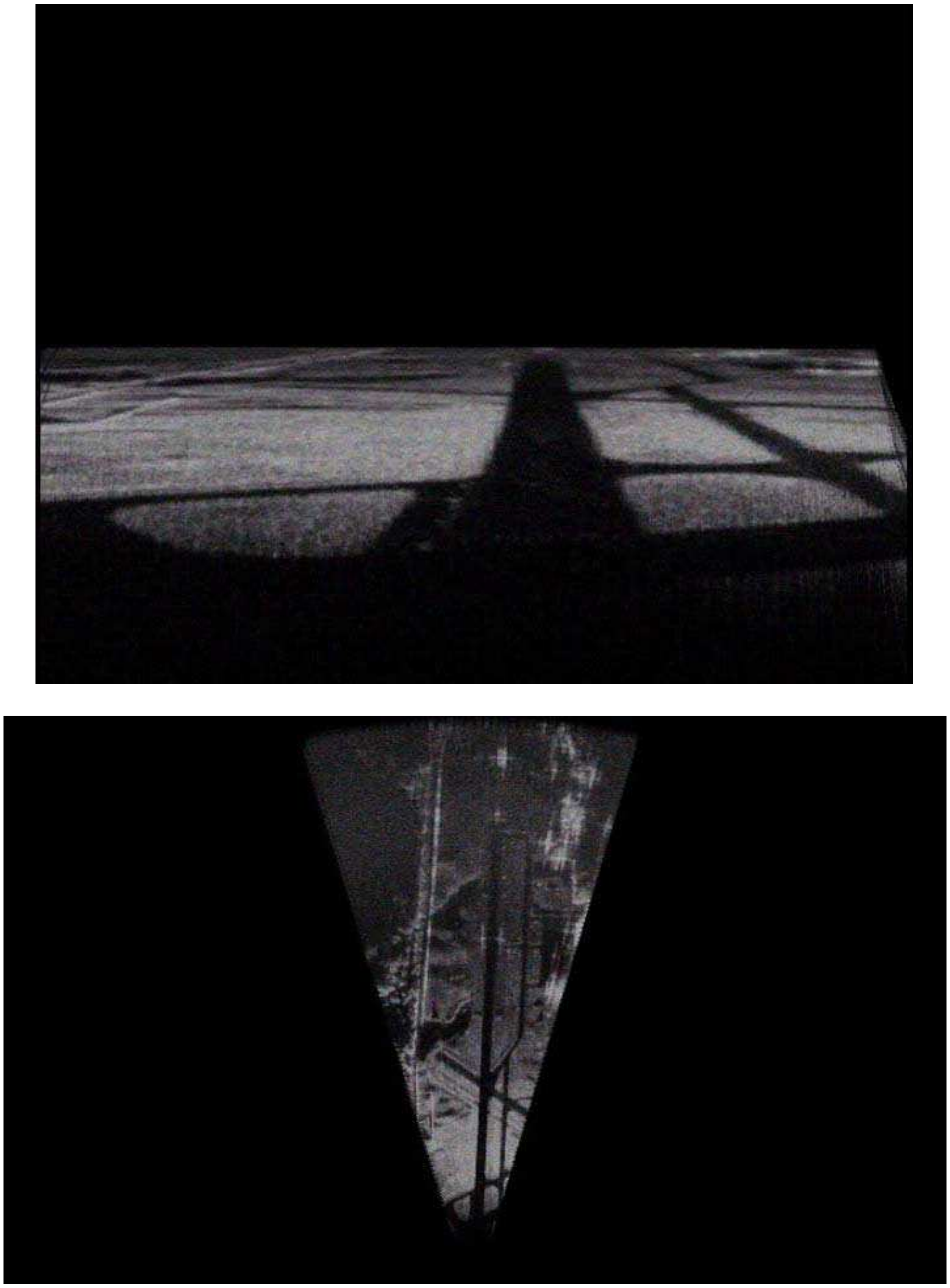

Figure 14. Runway image on approach after temporal processing

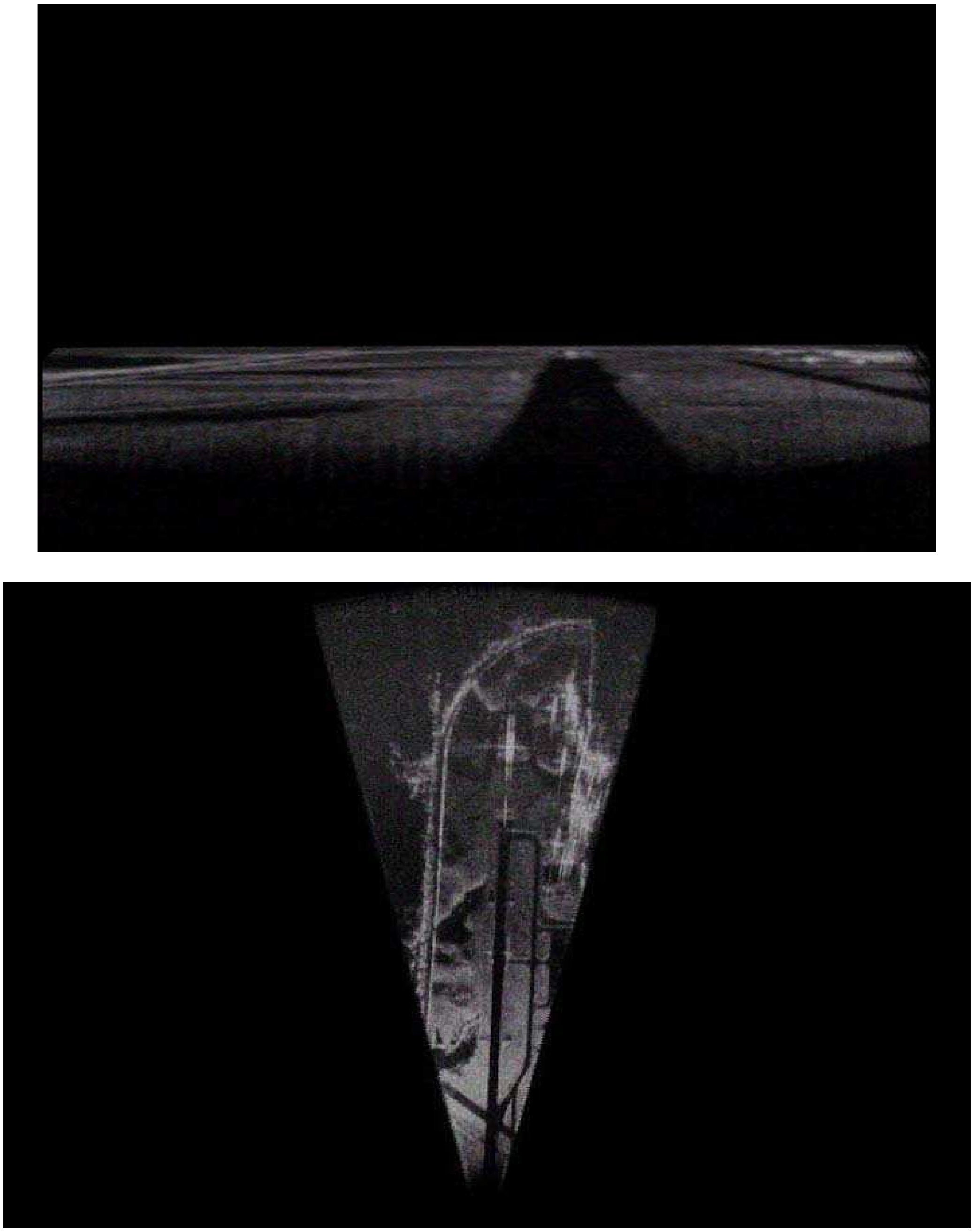

Figure 15. Runway image on approach after temporal processing