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Gordon E. Carlson

Missouri University of Science and Technology

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AN IMPROVED SINGLE FLIGHT TECHNIQUE FOR RADAR STEREO

Gordon E. Carlson
University of Missouri-Rolla
Rolla, Missouri

Abstract: An improved technique for obtaining stereo radar image pairs is described. The technique uses a unique combination of two different radar beam pattern characteristics. The resulting stereo radar images are illuminated from very nearly the same aircraft position which results in radar shadow and backscatter characteristics which are very similar and in improved image registration possibilities. The reduction in illumination angle and aircraft position differences is shown to be nearly an order of magnitude or more when compared with a previously proposed single flight technique which used two vertical fan beam patterns at different azimuth angles. As a related sidelight it is shown that this previous technique requires the two fan beam patterns to generate parallax on the images and thus can not be implemented with synthetic arrays squinted at two different squint angles.

Introduction

The generation of topographic maps requires a pair of stereo images which possess sufficient geometric parallax (image displacement difference due to terrain elevation) to permit the determination of the height of terrain points above a reference elevation plane. Parallax is illustrated in Fig. 1 for a pair of overlapping photographic images taken on a single flight. The image of the elevated terrain point A appears at point A_1 on image #1 and at point A_2 on image #2. The resulting parallax (D) is a function of the photographic base (B) and the altitudes of the aircraft (H) and the terrain point (h) above the reference plane. Therefore, the height of the terrain point above the reference plane can be determined from the flight parameters and the measured parallax.

The availability of parallax information in pairs of radar imagery due to the slant ranging characteristic of radar data acquisition has been recognized for many years.[1-5]

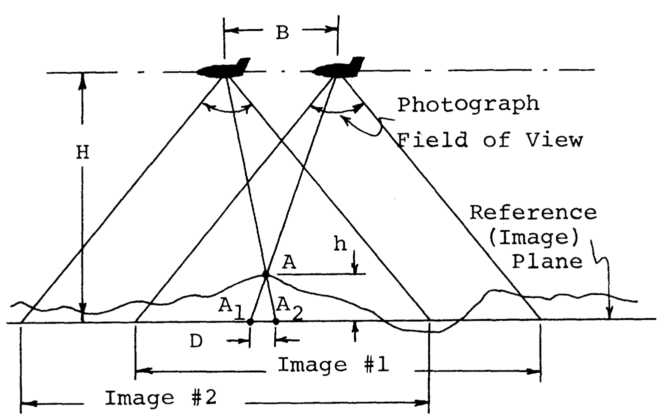

Fig. 1 Illustration of Image Parallax

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Existing implemented techniques for obtaining stereo radar image pairs utilize a side-looking radar beam and two flights at different elevation angles with respect to the terrain of interest to provide two images with different image displacements for elevated (or depressed) terrain points. While such radar image pairs are not central perspective pairs, the parallax information contained in them is sufficient to permit the construction of topographic maps by analytic stereoplotting techniques.[6-7] The requirement for two flights and the differences in radar shadows and radar backscatter characteristics due to the significantly different illumination angles are undesirable features.

Previously defined single flight techniques have considered two radar beams generated on a single flight with considerable azimuth angle separation between the two beams. It is shown in a later section of this paper that this requires two antennas which are physically slewed to the desired azimuth angles in order to obtain the required different image geomatries for parallax generation. This technique does eliminate the requirement for two flights; however, the radar illumination angle for the two images is still significantly different and the aircraft position separation when recording the two images is large.

An improved technique for obtaining stereo radar images, which uses two types of radar beam characteristics, is described in this paper. This technique has the advantage of illuminating the terrain point with both beams from nearly the same aircraft position while providing image geometry differences sufficient to provide useful parallax data. This means that radar shadows and backscatter characteristics are nearly the same on the two images and that relative image registration across the images is better due to the short distance travelled by the aircraft between the two image recordings. An example comparison of the two single flight techniques is shown.

Basic Radar Beam Geometry

Before discussing and comparing the various techniques for obtaining stereo radar image pairs, it is necessary to review basic radar beam geometry. The radar beams to be considered for all techniques will be assumed to be formed by linear phased arrays or synthetic arrays.[8] These types of antennas are used since they can give good azimuth resolution characteristics.

The beam pattern for a linear phased array which is phased to give a beam perpendicular to the array is shown in Fig. 2. It can be seen that the beam pattern is a fan beam lying in the plane perpendicular to the array which passes through the center of the array. This is also the beam pattern which results when a synthetic array is used in a side-looking (perpendicular to the flight path) mode.

Figs. 3 and 4 show the geometry associated with the data acquisition, raw radar data storage, and data conversion to ground range coordinates for the beam shown in Fig. 2. These sketches are shown for a horizontal linear phased array which is positioned at the angle 90-θ degrees with respect to the aircraft flight path. In Fig. 4a, the raw radar data has been imaged in slant range, azimuth angle coordinates. This data is reimaged using the appropriate hyperbolic sweep for the aircraft altitude above the reference plane (H) at the azimuth angle θ to give the

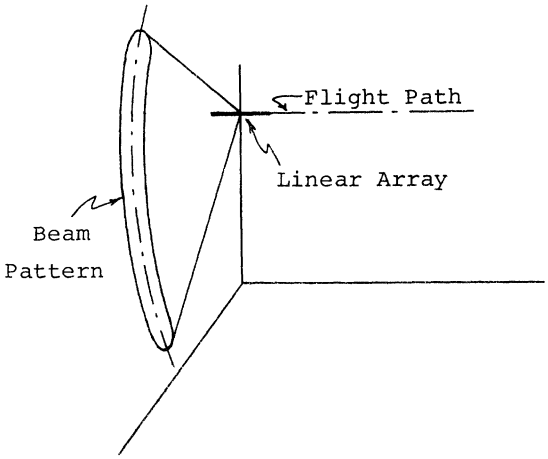


Fig. 2 Vertical Fan Radar Beam Pattern

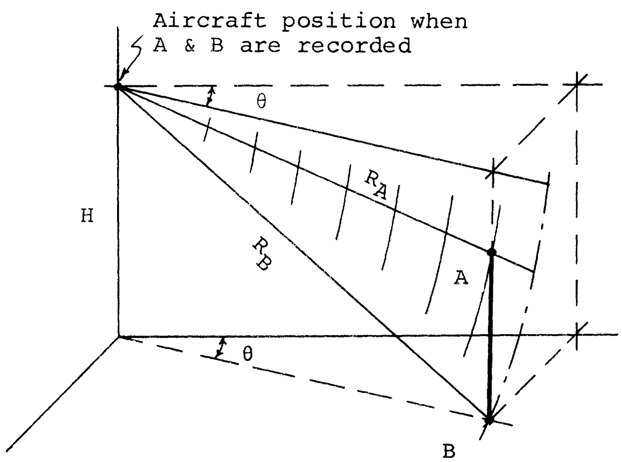
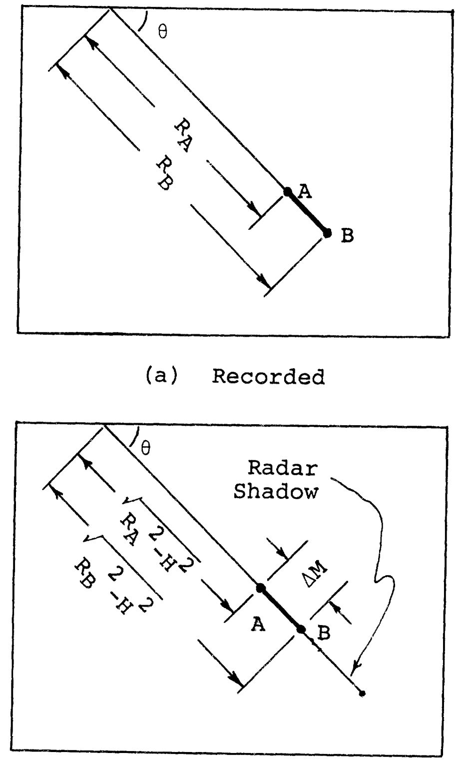


Fig. 3 Image Recording Geometry for a Vertical Fan Radar Beam at Azimuth Angle θ

image shown in Fig. 4b in ground range, azimuth angle coordinates. Note that points such as B which are on the reference plane are orthographically located on the resulting ground range image. Elevated (or depressed) points such as A are displaced from their orthographic location along the azimuth line defined by the angle θ. This displacement is due to the slant range characteristic of the radar data acquisition. Points in the plane



(a) Recorded

(b) Reimaged

Fig. 4 Recorded and Reimaged Radar Images Produced by a Vertical Fan Radar Beam at Azimuth Angle θ

of the beam behind the vertical object (with respect to the aircraft position) lie in the radar shadow of the vertical object. Therefore, the radar shadow on the resulting image is at the azimuth angle θ as shown in Fig. 4b. One comment should be made in regard to the sketches. The vertical object is shown excessively tall to exaggerate the displacement and shadow effects.

The beam pattern for a linear phased array which is phased to give a beam which is not perpendicular to the array is shown in Fig. 5. It can be seen that the beam pattern is a section of a cone. The apex of the cone is at the center of the array, and the cone angle ϕ is as shown on Fig. 5. This is also the beam pattern which results when a synthetic array is used in a squint (non-perpendicular to the flight path) mode.

Figs. 6 and 7 shown the geometry associated with the data acquisition, raw radar data storage, and data conversion to ground range coordinates for the conical beam shown in Fig. 5. These sketches are shown for a horizontal linear phased array which is positioned parallel to the flight path and has been phased to give the cone angle ϕ. In Fig. 7a, the raw radar data has been imaged in slant range, cone angle coordinates. This data is reimaged using a hyperbolic scan perpendicular to the flight path direction. The hyperbolic scan parameters are determined by the aircraft altitude (H) above the reference plane. This reimaging gives the image

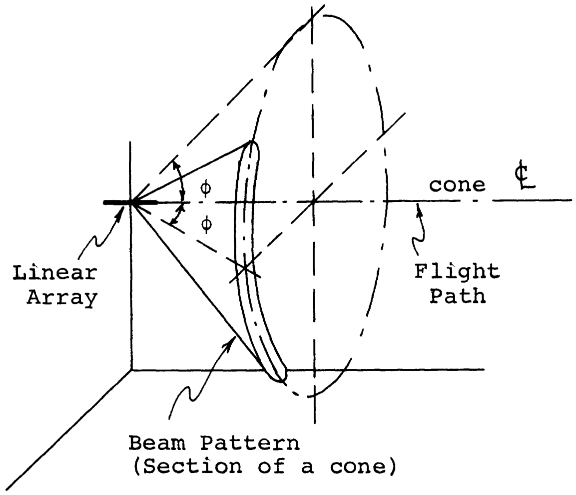


Fig. 5 Conical Radar Beam Pattern

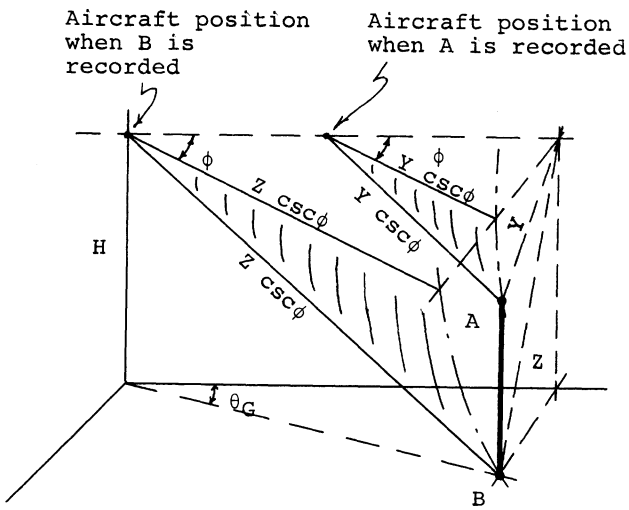


Fig. 6 Image Recording Geometry for a Conical Radar Beam with Cone Angle ϕ

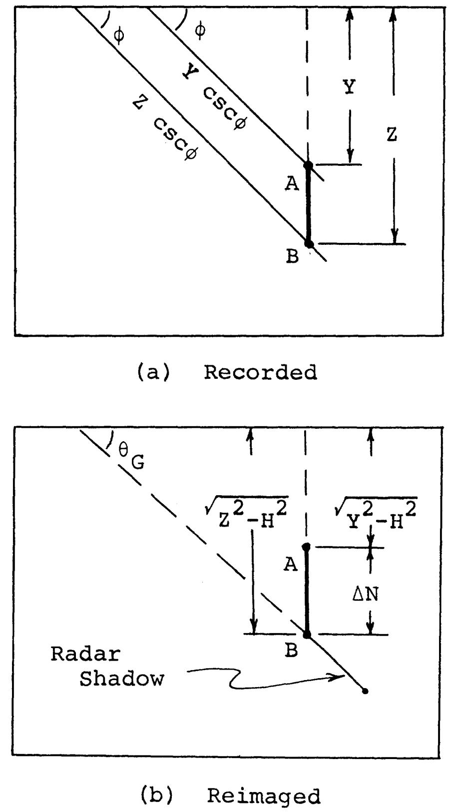


Fig. 7 Recorded and Reimaged Radar Images Produced by a Conical Radar Beam with Cone Angle ϕ

shown in Fig. 7b which is in ground range coordinates. Points on the reference plane, such as B, are orthographically located on the resulting ground range image. Elevated (or depressed) points such as A are displaced from their orthographic location by the distance ΔN in a direction perpendicular to the aircraft ground track due to the slant range, cone angle characteristic of the radar data acquisition. Note that ΔN does not depend on the cone angle ϕ used. A point by point consideration of the radar shadow of a vertical object shows that it lies at the azimuth angle $\theta_s = \cos^{-1}[\cos\phi \sec\delta]$ on the ground range image where ϕ is the cone angle and δ is the lookdown angle from the aircraft position to the terrain point. Therefore, the azimuth angle of the radar shadow does depend on the cone angle ϕ chosen.

Since δ decreases slightly as successively higher points of the vertical object are illuminated, θ_s increases slightly. This means that the radar shadow of a straight vertical object will be slightly curved on the resulting ground range image. This curvature will be quite small for normal vertical objects observed. The general form of the radar shadow (not drawn to scale) is shown in Fig. 7b. The vertical object is again shown excessively tall to exaggerate the displacement and shadow effects. This also greatly exaggerates the distance that the aircraft travels between the illumination of the bottom and the top of the vertical object.

Previous Techniques

The presently used technique which has been implemented for obtaining stereo radar image pairs to be used for topographic map generation utilizes a side-looking radar and two flights at different elevation angles with respect to the terrain being mapped as shown in an elevation view in Fig. 8. The resulting two images of a single vertical object are shown in Fig. 9. The image displacement difference for the top of the object (point A) as well as the difference in the radar shadows is apparent. The difference in the radar shadows, the difference in radar backscatter characteristics and the differences in image registration across the map due to

the use of two flights are disadvantages of this method which degrade the stereo viewability and topographic measurement. Also, it is a disadvantage to require two flights from a time and cost standpoint.

The generation of stereo radar image pairs on a single flight with two radar vertical fan beams at different azimuth angles has been previously proposed. The concept is illustrated in a plan view in Fig. 10 and the two radar images which results are shown superimposed in Fig. 11. This technique would eliminate the two flight requirement, but the difference in illumination angle (θ_o) as shown in Fig. 10 (which results in the radar shadow difference shown in Fig. 11 and in radar backscatter characteristics differences) and the aircraft position separation (ΔL) when recording the two images are still large.

One other comment with respect to this proposed single flight technique is in order. From a resolution standpoint it would be desirable if the two radar beams could be generated by synthetic arrays squinted at two different squint angles. However, the results shown in Figs. 6 and 7 show that the image displacement of an elevated (or depressed) terrain point, such as point A, is the same regardless of the squint angle used. Therefore, the resulting two images do not have any parallax information and cannot be used for determination of terrain point elevations. Thus, this proposed technique only works if two fan beams, such as can be generated by two horizontal linear phased arrays at different azimuth angles with respect to the aircraft flight path, are used.

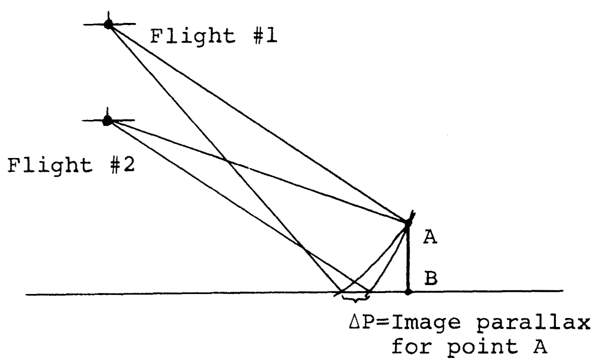


Fig. 8 Recording Flight Geometry for Two Flight Technique

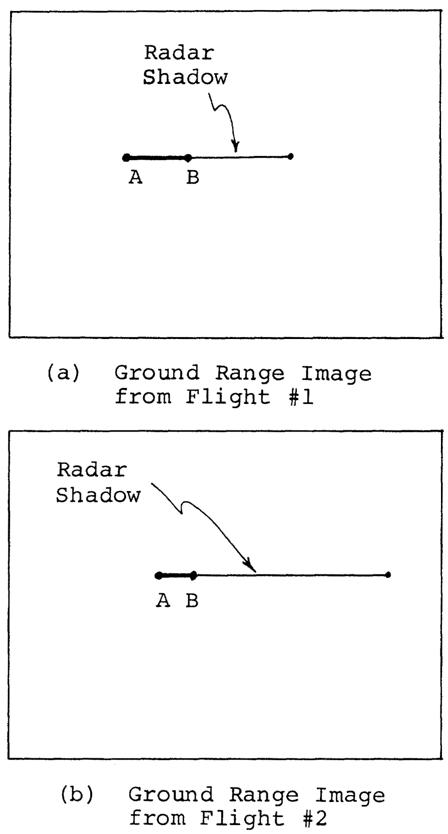


Fig. 9 Radar Image Pair for Two Flight Technique

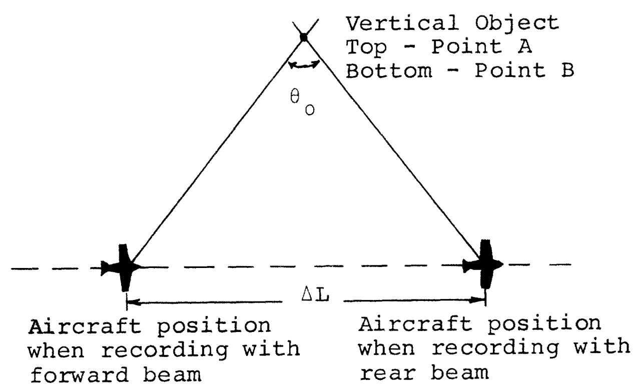


Fig. 10 Recording Flight Geometry for Previous Single Flight Technique

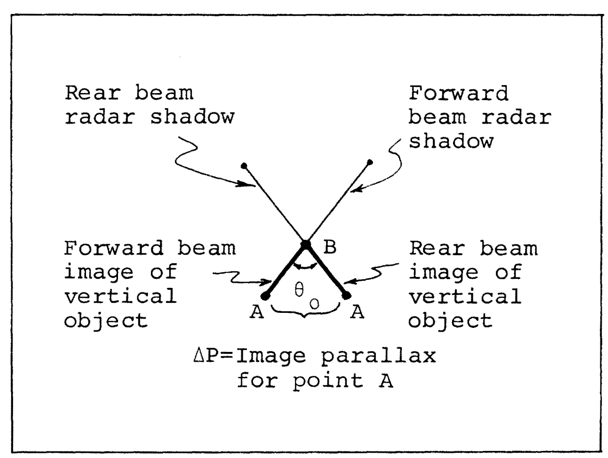


Fig. 11 Superimposed Radar Image Pair for Previous Single Flight Technique

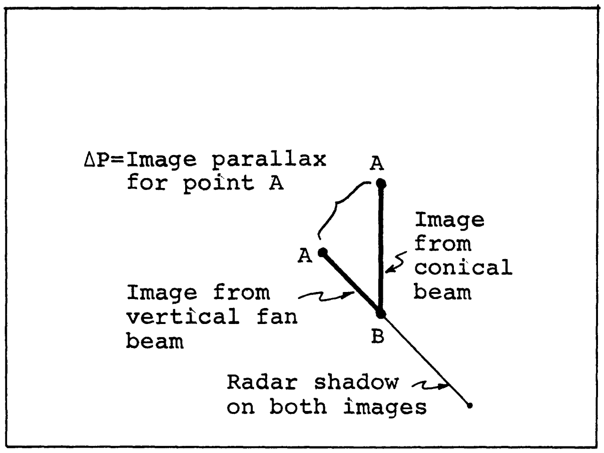


Fig. 12 Superimposed Radar Image Pair for the Improved Single Flight Technique

Improved Single Flight Technique

An improved technique for obtaining stereo radar image pairs is now described. This technique uses one fan beam generated by a horizontal linear array at an angle of 90-θ degrees with respect to the aircraft flight path as was shown in Fig. 3. The second radar beam is a conical beam generated by a horizontal linear array parallel to the aircraft flight path with cone angle ϕ as was shown in Fig. 6. The superposition of the resulting two ground range images is shown in Fig. 12.

The superimposed images shown are those which would result for an object at the position in the map swath where a point on the reference plane is illuminated at the same time by both beams. θ and ϕ can be chosen to locate this point at any desired cross track ground range as defined to be the perpendicular distance on the ground range image between the flight path ground track and the terrain point. The resulting parallax for the elevated point A is shown. Also, the radar shadows for both images are shown and lie in the same direction and are very nearly the same length. The radar shadow on the image produced by the conical radar beam would actually have a small amount of curvature as previously indicated. However, for normal terrain height variations, this curvature is too small to be shown on the sketch. Since the bottom of the vertical object is illuminated from the same aircraft position by both radar beams and the top of the vertical object is illuminated from very nearly the same aircraft position, then radar backscatter characteristics are also very nearly the same for both images.

Points at cross track ground ranges other than that indicated above will not be illuminated at exactly the same time by both beams. Therefore, the illumination of the two images will come from slightly different aircraft positions with resulting slightly different illumination angles. By chosing θ and ϕ appropriately, the aircraft position differences will be of opposite sign at the near and far edges (with respect to the flight path) of the map swath and can thus be minimized. This in turn minimizes radar shadow, radar backscatter characteristic, and aircraft position differences between the two images. This will give images with improved stereo viewability, due to similar radar shadows and backscatter, and better image registration across the map, due to improved relative aircraft position stability.

Example image parameters for this improved technique are shown in Table I for a particular set of parameters. Also included, for comparison purposes, are example image parameters for the other previously proposed single flight technique. To make this comparison, the previously proposed single flight technique is assumed to be implemented by replacing the conical beam of the improved technique with a vertical fan beam looking perpendicular to the aircraft flight path. This results in object images with the same geometries for both techniques and thus in the same parallax for both techniques as shown in Table I. It can be seen from the comparison shown, that the illumination angle and aircraft position differences are nearly an order of magnitude or more smaller for the improved technique. Therefore, the advantages of the improved technique are of sufficient magnitude to improve the resulting stereo images.

Determination of the terrain height measuring accuracy possible with images obtained by the improved single flight technique (as well as any of the other radar techniques) is hampered by a lack of controlled experimental work with stereo radar images. From a parallax measurement accuracy standpoint (neglecting imaging and aircraft attitude error sources), a lower limit on the accuracy attainable would be that the parallax must be at least 20% of the resolution on the radar image which is an accepted limit for photographic images. However, due to the nature of radar images, investigators working with stereo radar images feel that the minimum parallax required is probably a larger percentage of the resolution. Very little attempt has been made to quantify this minimum parallax requirement. Measurements made two flight radar stereo images in uncontrolled experiments in which imaging and aircraft attitude errors are also included have shown parallax requirements of greater than the resolution.

To indicate a theoretical limit on the height measuring capability of the improved single flight technique it is assumed that a reasonable parallax requirement may be 50% of the radar image resolution. The results can be easily scaled if another assumption is more appropriate for particular radar imaging. The parameters shown in Table I are used which gives a maximum range of 29900 feet and a minimum range of 20600 feet. In addition, the projected length of the arrays is assumed to be 20 feet and the radar frequency is assumed to be 35 GH_z (K_a band). With these assumptions, the resolution is 29 feet at the inside edge of the image and is 42 feet at the outside edge of the image. Using the 50% requirement and the parallax sensitivities shown in Table I gives a height measuring accuracy of 30.4 feet at the inside edge of the image and 79.6 feet at the outside edge

TABLE I

EXAMPLE COMPARISON OF IMPROVED SINGLE FLIGHT TECHNIQUE WITH EQUIVALENT PREVIOUS SINGLE FLIGHT TECHNIQUE

	Improved Technique	Previous Technique
System Parameters		
Image Width	2 miles	2 miles
Aircraft Altitude	14727 ft.	14727 ft.
Look down angle (Beam #1)	29.5°-45.6°	29.5°-45.6°
θ_1	65°	65°
Look down angle (Beam #2)	30°-45°	32°-48.5°
ϕ_2	70.8°	--
θ_2	--	90°
Image Parameters		
Parallax sensitivity (Parallax/Object height)	0.264-0.477	0.264-0.477
Aircraft position difference	0-1500	6090-11000
Illumination Angle difference	0°-2.8°	17.5°-21.6°

of the image for the particular system parameters chosen. The theoretical accuracies would be smaller for lower aircraft altitudes with narrower image widths and larger for higher aircraft altitudes with wider image widths.

Other factors which will affect the height measuring accuracy are errors in the knowledge of aircraft attitude and errors in the image formation. The improved single flight technique does have an advantage here since the images are taken on a single flight with very little separation between the two aircraft positions. This permits better knowledge of relative aircraft positions.

Summary

An improved technique for obtaining stereo radar image pairs on a single flight has been described. This technique uses two linear phased arrays on a single aircraft which are phased such that one gives a vertical fan beam pattern and the second gives a conical beam pattern. It was shown that utilization of these two beam patterns can give stereo radar image pairs with very similar radar shadow and radar backscatter characteristics across the resulting two images. Also illumination is from very nearly the same aircraft position. Thus, stereo viewability and relative image registration across the map is improved. The magnitude of the improvement in illumination angle difference and aircraft position difference with the new technique was shown to be nearly an order of magnitude or more for the example parameters chosen.

As a related sidelight, it was also shown that the previously proposed single flight technique for stereo radar imaging requires two vertical fan radar beam patterns and cannot be implemented with synthetic arrays which are squinted to look two different directions since no image parallax results in this case.

Acknowledgment

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