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JPL Publication 89-44

P-143

The Browse File of NASA/JPL Quick-Look Radar Images From the Loch Linnhe 1989 Experiment

Walter E. Brown, Jr.
Editor

(NASA-CR-186855) THE BROWSE FILE OF NASA/JPL QUICK-LOOK RADAR IMAGES FROM THE LOCH LINNHE 1989 EXPERIMENT (JPL) 143 p CSCL 05B G3/82

N90-26701

Unclas 0293533

November 15, 1989

Prepared for

Defense Advanced Research Projects Agency

and

National Aeronautics and Space Administration

by

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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Overleaf: The NASA/ARC DC-8 was the platform for the JPL AIRSAR. The aft antenna array was used for standard SAR image acquisition, and the forward antenna array was used for along-track interferometry.

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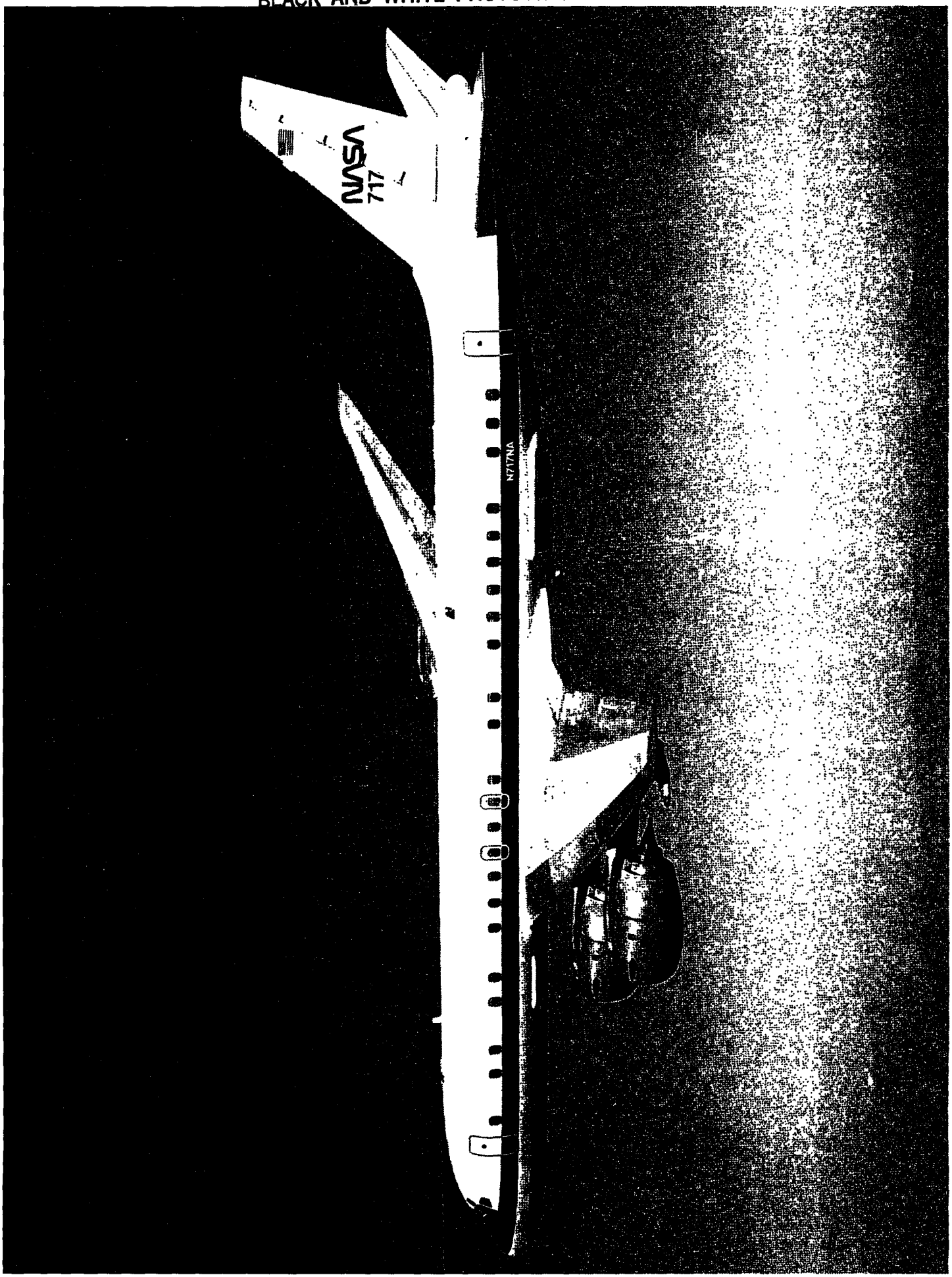

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the Defense Advanced Research Projects Agency and the National Aeronautics and Space Administration.

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Acknowledgment

We wish to thank David Fulton for his help in coordinating this material.

Abstract

During August of 1989, the JPL Aircraft Synthetic Aperture Radar (AIRSAR) was deployed to Scotland to obtain radar imagery of ship wakes generated in Loch Linnhe. These observations were part of a joint United States and United Kingdom experiment to study the internal waves generated by ships under partially controlled conditions. The AIRSAR was mounted on the NASA/Ames Research Center DC-8 aircraft. The data-acquisition sequence consisted of 8 flights, each about 6 hours in duration, wherein 24 observations of the instrumented site were made on each flight.

This Browse File provides the experimenters with a reference of the real-time imagery—approximately 100 images—obtained on the 38-deg track. These radar images are copies of those obtained at the time of observation and show the general geometry of the ship-wake features. To speed up processing during this flight, the images were all processed around zero Doppler, and thus azimuth ambiguities often occur when the drift angle (yaw) exceeded a few degrees. However, even with the various shortcomings, we believe the experimenter will find the Browse File useful in establishing a basis for further investigation.

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Flight Operations and Data Acquisition

Walter E. Brown, Jr.

Introduction

During August of 1989, the Jet Propulsion Laboratory (JPL) Aircraft Synthetic Aperture Radar (AIRSAR) was deployed to Scotland to obtain radar imagery of ship wakes generated in Loch Linnhe. These observations were part of a joint United States and United Kingdom experiment to study the internal waves generated by ships under partially controlled conditions. The AIRSAR was mounted on the National Aeronautics and Space Administration (NASA)/Ames Research Center (ARC) DC-8 aircraft. The data-acquisition sequence consisted of eight flights. Each flight lasted 6 hours and consisted of 12 closed-loop courses. The first pass of this course (the "front side") was on a 39-degree track and the second was on a 219-degree track, resulting in 24 observations of the instrumented site on each flight.

The success of the mission was the result of contributions from a large number of individuals from several organizations. At the Defense Advanced Research Projects Agency (DARPA), Dr. Ron Repka and Dr. Tom Taylor were principally responsible for sponsoring the JPL effort, and at NASA Headquarters, Dr. Shelby Tilford, Dr. Wes Huntress, and Dr. Diane Wickland provided the coordination necessary to allow the mission to occur. Those directly involved with the JPL Radar and the DC-8 deployment are listed in Table 1.

This Browse File provides the experimenters with a reference of the real-time imagery—approximately 100 images—obtained during the "front-side" observations. These radar images are copies of those obtained at the time of observation and show the general geometry of the ship-wake features. To speed up processing during the flight, the images were all processed around zero Doppler, and thus azimuth ambiguities often occur when the drift angle (yaw) exceeded a few degrees. However, even with the various shortcomings, we believe the experimenter will find the Browse File useful in establishing a basis for further investigation. The Loch Linnhe quick-look imagery was obtained by the JPL Aircraft SAR during the periods August 10 through 14 and August 24 through 28, 1989.

The imagery was generated by the flight correlator on board the NASA/ARC DC-8 aircraft within about 8 minutes following data acquisition.

Table 1. Individuals directly involved with the JPL radar and DC-8 deployment

JPL	ARC	NSI Technology Services
SAR Flight Crew	**DC-8 Flight Crew**	**DC-8 Ground Crew**
Brown, W.	Tiffany, G.	Mitz, E.
Miller, T.	Hall, W.	McKinnon, D.
Fiechter, W.	Baker, D.	Davis, S.
Carande, R.	Call, E.	Horvat, J.
Guerra, A.	Rager, T.	Kahl, C.
Kobrick, M.	Hoss, W.	Ristrum, P.
McCluskey, J.	Moniz, G.	Lakowski, M.
Sato, T.	Morrison, R.	Thomas, K.
Skotnicki, W.	Petersen, E.	Zuberer, H.
Wheeler, K.	Morris, R.	Alvarez, P.
	Jaynes, D.	Reynolds, R.
SAR Support	Wooten, D.	Roberts, G.
Li, F.	Scofield, C.	Harner, G.
Blakely, R.	Reller, J.	
Gilstrap, J.	DeGreef, L.	
Smith, A.		
Olivieri, L.	**Sheet Metal**	
Parkhurst, A.	Casey, M.	
Goldstein, R.	Christianson, D.	
Norikane, L.		
Zebker, H.		
Weirick, J.		
SAR Calibration		
Lou, Y.		
Holt, J.		
Werner, C.		
Shen, Y.		
Freeman, A.		

Data Acquisition

The data were obtained by the JPL AIRSAR sensor, the key parameters of which are given in Table 2. The sensor operates on three frequencies (P-, L-, and C-bands) simultaneously, transmitting alternately horizontal (H) and vertical (V) polarizations; both polarized echoes are received simultaneously. In the designation CHV, for example, C refers to the band, H refers to horizontal transmit polarization, and V refers to vertical receive polarization.

The mode selected for data acquisition was 40 megahertz bandwidth and 5 microseconds pulsewidth.

Table 2. Key AIRSAR sensor parameters

Parameter	P-(or UHF-) Band	L-Band	C-Band
Frequency, GHz	0.45	1.26	5.31
Wavelength, cm	67	23	5.7
Polarization	VV, HH, VH, HV	VV, HH, VH, HV	VV, HH, VH, HV
Bandwidth, MHz	20, 40	20, 40	20, 40
Range resolution, m	7.5, 3.75	7.5, 3.75	7.5, 3.75
Azimuth resolution, m	2	2	2
Noise equivalent sigma zero, dB at 40-deg incidence angle	-47	-57	-41
Pulse width, μs	5, 10	5, 10	5, 10
Pulse-repetition frequency, pulses/s	17/25 or 34/25 * ground speed		
Peak power to antenna, kW	1	6	0.9
Quantization, bits	8	8	8
Data-acquisition burst rate, Mbytes/s	180	180	180
Swath buffer, samples	8192	8192	8192
Swath width (max), km	17	17	17
Swath width (nom), km	8, 4	8, 4	8, 4
Data storage rate, Mbytes/s	10	10	10
Range of incidence angles, deg	0 to 75	0 to 75	0 to 75

The data-acquisition conditions are summarized in Table 3, and the sequence of images taken in real time is given in Table 4. On each primary pass over the instrumented site at an aircraft track angle of 39 degrees, the flight correlator was turned on 30 seconds prior to the closest point of approach (CPA) and collected data for a total of about 65 seconds. The correlation of a preselected frequency and polarization was then initiated. About 10 minutes later, the image was available on a transparency, either as a positive or a negative. The matrix in Table 4 shows the frequencies and polarizations chosen for each pass. The images are shown in the Appendix.

At the end of the flight, some data were transferred from the high-density digital tapes, and additional imagery was generated.

Table 3. Summary of the data-acquisition conditions

Date	Day	Code	Incidence Angles[a], deg
890809	221	UL1B	25, 40
890810	222	UL2C	25, 55
890812	224	UL2A	40, 25
890813	225	UL1C	25, 55
890824	236	LL1C	25, 55
890825	237	LL2A	40, 25
890827	239	LL1C	25, 55
890828	240	LL2C	25, 25

[a]The first number was the angle assigned for the first six aircraft passes; the second number is the angle for passes 7 through 12.

Table 4. Matrix of the image data processed in near-real time on board the DC-8 aircraft.

Day, Code and Date	Aircraft Pass Number											
	1	2	3	4	5	6	7	8	9	10	11	12
221 UL1B 09 AUG	CV[a]	LV	PV	CH	LH	CV	CV	CV	PV	PV	PV	PV
222 UL2C 10 AUG	CV	CV	PV	LV	PV	LV	LV	PV	_[b]	CV	PV	PVH
224 UL2A 12 AUG	PV	PH	LV	LH	CV	CH	PV	PH	LV	LH	LV	PV
225 UL1C 13 AUG	PV	PV	PVH	LVH	LV	PV	LVH	LV	PV	CV	PV	PV
236 LL1C 24 AUG	PV	PH	LV	LH	PV	PH	PV	PV	LV	LV	PV	PV
237 LL2A 25 AUG	PV	PH	LV	LH	CV	PV	LV	LV	PV	LV	LV	LV
239 LL1C 27 AUG	PV	CV	LH	LV	PV	PH	LV	LV	LV	LV	PV	PV
240 LL2C 28 AUG	LV	PV	LV	LV	LV	LV	LV	LV	LV	LV	LV	LV

[a]A single-letter polarization indicates identical polarization was used for both transmit and receive.
[b]No data.

Image Geometry

In all the imagery, near range is at the top, and the identification is at the left. The DC-8 aircraft flew from right to left, and the radar looked to the left. The image has been converted to ground range with a pixel size of 6 × 6 meters. Approximate incident angles are shown at both the left and right sides of the image. The accuracy of the conversion to this scale is a function of the true altitude over sea level. Usually the DC-8 was over land at the time of CPA; hence, the radar altimeter was not usable. The barometric altimeter was set at take off, and its measurement of pressure altitude was a function of local weather. Generally, in comparisons between the radar altimeter and the barometric altimeter over the ocean just prior to a day's flight sequence, the pressure altitude readings and those of the radar altimeter were within 500 feet of each other. Therefore, in those cases where the altitude was estimated, incidence-angle errors of about 1 degree occurred at 55 degrees incidence angle and errors of 2.5 degrees occurred at 25 degrees incidence angle. A more accurate estimate can usually be made by using the planned incidence angle for the observation because, with the distance-measurement equipment update, we found the DC-8 was within 0.1 minute of the Global Positioning Satellite (GPS) indication of latitude and longitude. Thus, in those cases where the target site was used to set the incidence-angle scale, the estimate was within 1 degree.

In these copies of the quick-look imagery, there has been no attempt to correct for amplitude or geometric variations. The imagery simply represents a first look at the data.

The JPL Near-Real-Time Aircraft Flight Correlator

Richard E. Carande

Prior to the Loch Linnhe II experiments, a high-priority goal was to upgrade the AIRSAR by adding near-real-time processing of the acquired SAR data. Without this ability, it would be several days or even weeks before any JPL imagery could be provided by the ground data processor at JPL. The ability to assess the performance of the radar by providing quick feedback on the visibility of features would contribute greatly toward assuring a successful experiment.

To meet this goal, JPL developed an onboard processor using a microcomputer outfitted with a fast-array processor, a radar interface, and display and hardcopy devices. This was the near-real-time onboard processor for correlation of the aircraft SAR data. Within 10 minutes of data acquisition, a ground-range corrected image could be processed and displayed. A hardcopy (positive or negative transparency) could be available in less than 2 minutes. The following is a brief description of this system, which is known as the Aircraft Flight Correlator.

Hardware

Figure 1 is an overview of the hardware architecture with notations that, with the text that follows, will allow investigators to duplicate the system. The microcomputer used is a MicroVAX III CPU in a custom configuration. The MicroVAX has three CDC Sabre 1.2-gigabyte disks, an HP nine-track tape drive, an HP printer, a Lasertechniques image printer, a Calcomp display system, and an array processor.

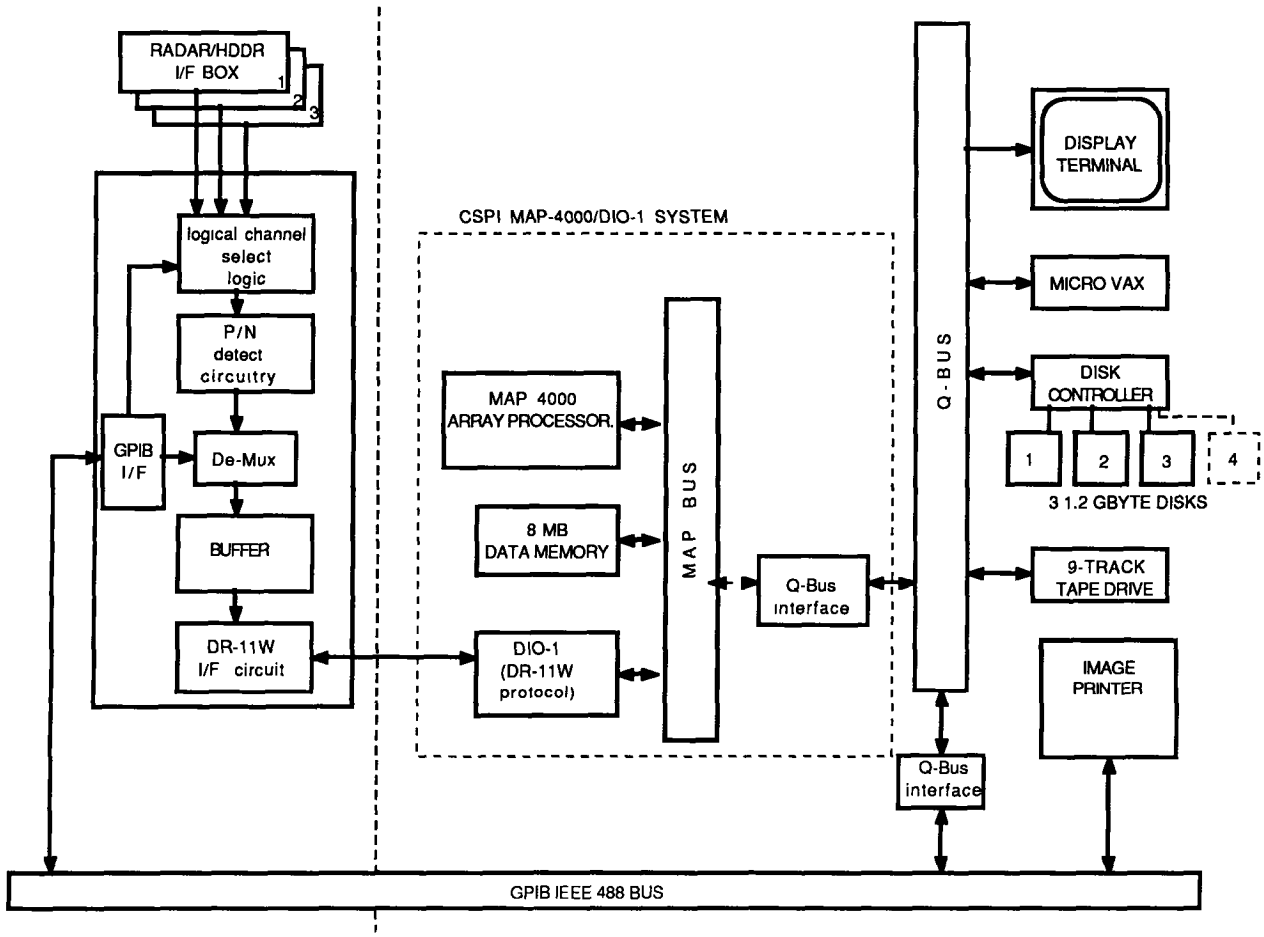

Figure 1. Aircraft Flight Correlator configuration

The equipment, excluding the printers, is housed in a standard DC-8 aircraft equipment rack.

The array processor is the 40-megaflop MAP-4000 Applications Accelerator made by CSPI with 8 megabytes of memory and a DIO card that allows external I/O using a DR11W protocol at rates up to 10 megabytes/second. Acquisition of data in real time is made possible via the interface box. This custom box of digital equipment is controlled via an IEEE 488 (GPIB) bus and serves as the interface between the radar digital system and the DIO in the MAP-4000. The interface box may be set up to demultiplex and SYNC align any one of the 12 individual radar-data channels or pass all 12 channels. Included in this data is the radar "header" information. The interface box may also be used as an interface to the high-density digital recorder for off-line processing.

Software

The Aircraft Flight Correlator is programmed in FORTRAN. The subroutines that run on the array processor are also programmed in FORTRAN with calls to scientific subroutines provided by CSPI.

Transfer of data in real time is accomplished by buffering large chunks of data between the interface box and the MAP-4000 memory. Simultaneously, double buffering is used to transfer data from the array processor memory to the MicroVAX disk. After 68 seconds of data have been acquired, processing may begin.

The SAR processing software takes advantage of the relatively large memory available on the array processor (8 megabytes) to perform all processing tasks in the memory with no buffering to disks. Typically, it is this disk buffering that causes most SAR processors to be I/O bound; the Aircraft Flight Correlator, however, is bound by the speed of the CPU.

The first calculations performed by the processor decode the radar header information and determine the proper range and azimuth-reference functions. In range, a single reference function is used. The basebanded complex conjugate of the Fourier transform of the range-reference function is stored in the array processor's memory. In azimuth, four adjacent single-look reference functions of a maximum length of 256 points (up to 1/4 Doppler bandwidth) are created. Each is zero padded, Fourier transformed (512 points), and complex conjugated. The resulting four 512-point vectors are combined to form a single 512-point composite azimuth-transfer function along with two numbers indicating the starting frequency of the lowest frequency of the four looks and the look bandwidth. The azimuth-reference functions are updated every eight range bins; therefore, 128 composite azimuth-transfer functions of 512 complex points each are calculated and stored in the array processor's memory. This set of transfer functions is used to process the entire scene.

The processor works on one "frame" of data at a time. A frame of data corresponds to 256 range lines. No presumming is performed. A frame of raw data is read from the disk to the array processor's memory and range compressed one line at a time. Each range-compressed line is written to the corner-turn array in azimuth order. The corner-turn array is two frames in size (4 megabytes), and holds the current range-compressed frame and the previous range-compressed frame. The azimuth-migration correction is implemented; this necessitates zero-Doppler azimuth processing for reasonable azimuth compression. (Upgrading the

processor to include range-migration correction is currently taking place.) Each line has a 512-point FFT taken and is multiplied by the correct composite azimuth-transfer function. The frequency bandwidth of each look is extracted and zero padded as necessary to form a 128-element vector. Each vector in turn goes through an inverse FFT, and 64 points are kept. The complex looks are detected (converted from complex to real magnitude), and adjacent pixels are summed 4:1 or 2:1, depending on whether the radar is in the 20-megahertz or 40-megahertz mode, respectively. The compressed looks are offset and added to a multilook array in corner-turn fashion so the data is back in range order. The last quarter of the multilook array has had contributions from four input frames, and is now completely processed. The MicroVAX reads this data and writes the floating point image to disk. The next frame of raw data is then read. Up to 80 input frames may be processed: about 68 seconds of data or about 14 kilometers along track.

Once a scene is processed, it may be displayed by scaling and converting to a byte image. The display program reads the associated header information and displays the image in either slant or ground range with incidence-angle ticks on the sides. This image can be directly printed out on the Lasertechniques image printer. All the prints shown in this publication were produced on the Lasertechniques printer.

External Calibration Devices Deployment

Yunling Lou

External calibration devices were deployed on site to support the JPL airborne SAR deployment at Loch Linnhe this past August. The calibration devices deployed included six 8-foot trihedral corner reflectors and seven radar transponders, three L-band Polarimetric Active Radar Calibrators (PARCs), and four C-band PARCs (three standard PARCs plus an old PARC). These devices were deployed according to the External Calibration Plan (Reference 1) with the relocation of one of the corner reflector sites.

Hardware Deployment

The 8-foot corner reflectors were made of perforated aluminum panels and were air lifted directly to Fort William, Scotland, from Norton Air Force Base in San Bernardino, California, via Military Airlift Command. This airlift was arranged by Jerry Belyea of Decision-Science Applications, Inc. The seven PARCs were air freighted via commercial airlines to Prestwick, Scotland, and trucked to Fort William. The sites were negotiated by Derek Kenward and Trevor Smith of Royal Aerospace Establishment (RAE). The JPL deployment team consisted of John Holt, Charlie Werner, Tony Freeman, and the author. The team was based in a trailer at the Underwater Center in Fort William; the trailer was thoughtfully provided by RAE.

Calibration Sites

Figure 2 is a general map of the loch showing the location of each site by the identification numbers as follow: The six corner reflectors were located at J1 through J6 for the upper-loch flights, and the PARCs were located at P1 and P2 for the lower-loch flights. Figures 3, 4, and 5 show the locations in greater detail. Table 5 gives the locations in longitude and latitude.

The sites for the corner reflectors and the PARCs were surveyed in the first week of August, and all six corner reflectors were deployed in the first week of August. The PARCs were deployed on the 9th, 10th, 24th, 25th, 27th, and 28th of August, just before the flights on those days. The PARCs, with serial numbers 1 through 3, were deployed in pairs. Serial No. 1 of L- and C-band was deployed at the same location, and serial No. 2 of L- and C-band was deployed approximately 50 meters

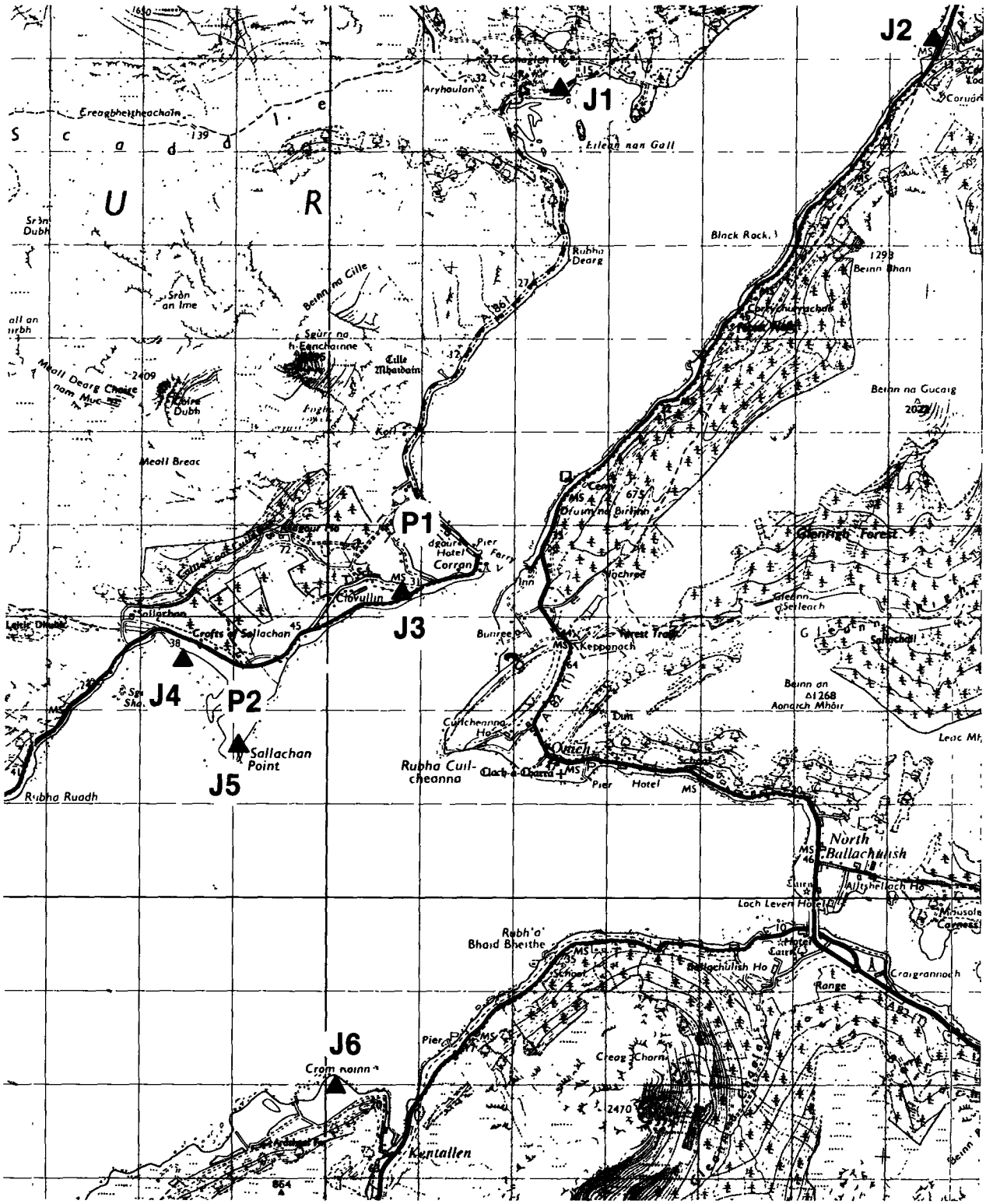

Figure 2. General map of the area at a scale of 1:63,360. Reproduced from the 1986 Ordnance Survey map with the permission of the Controller of Her Majesty's Stationery Office, © Copyright.

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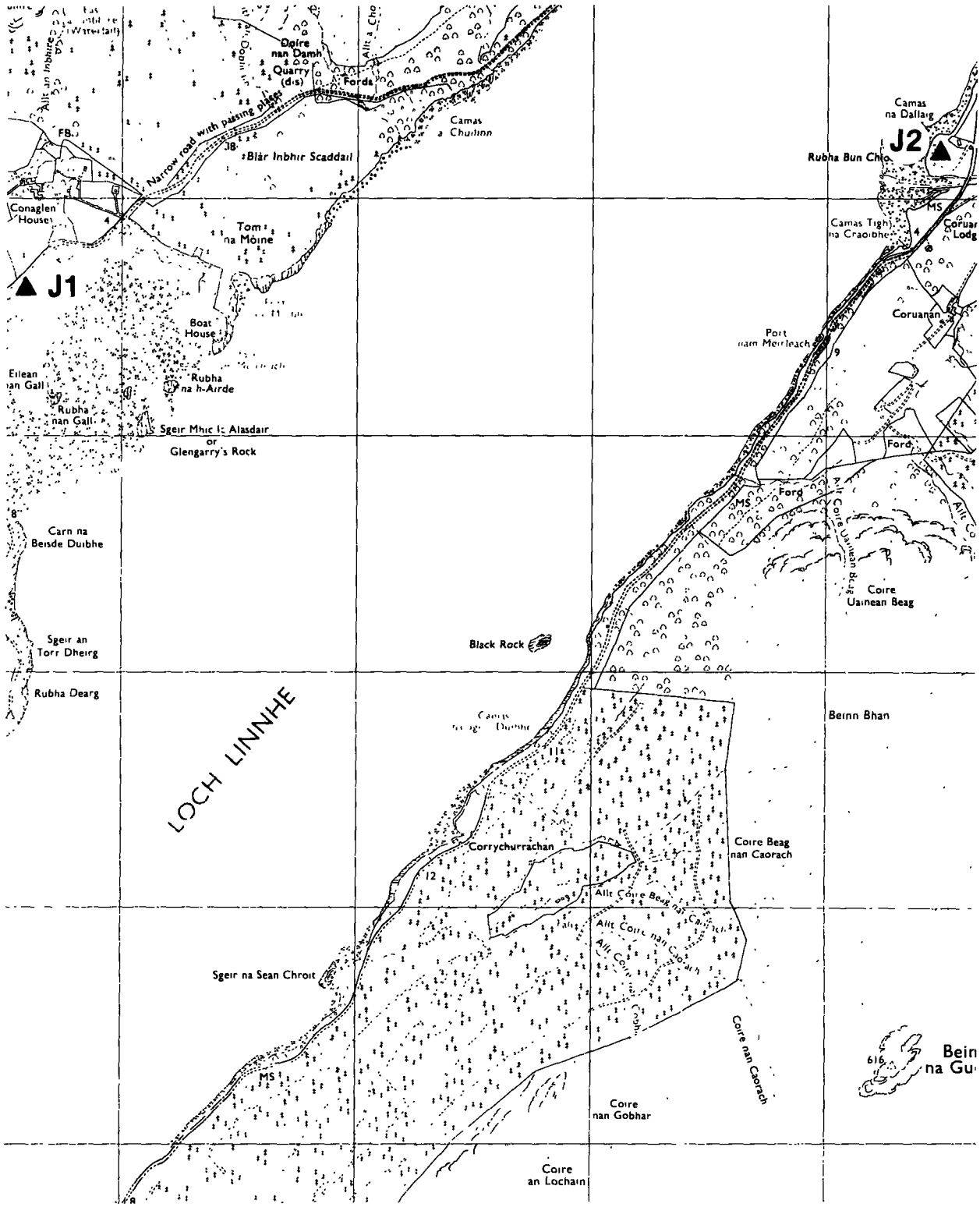

Figure 3. Upper-loch locations of J1 and J2 at a scale of 1:25,000. Reproduced from the 1979 Ordnance Survey map with the permission of the Controller of Her Majesty's Stationery Office, © Copyright.

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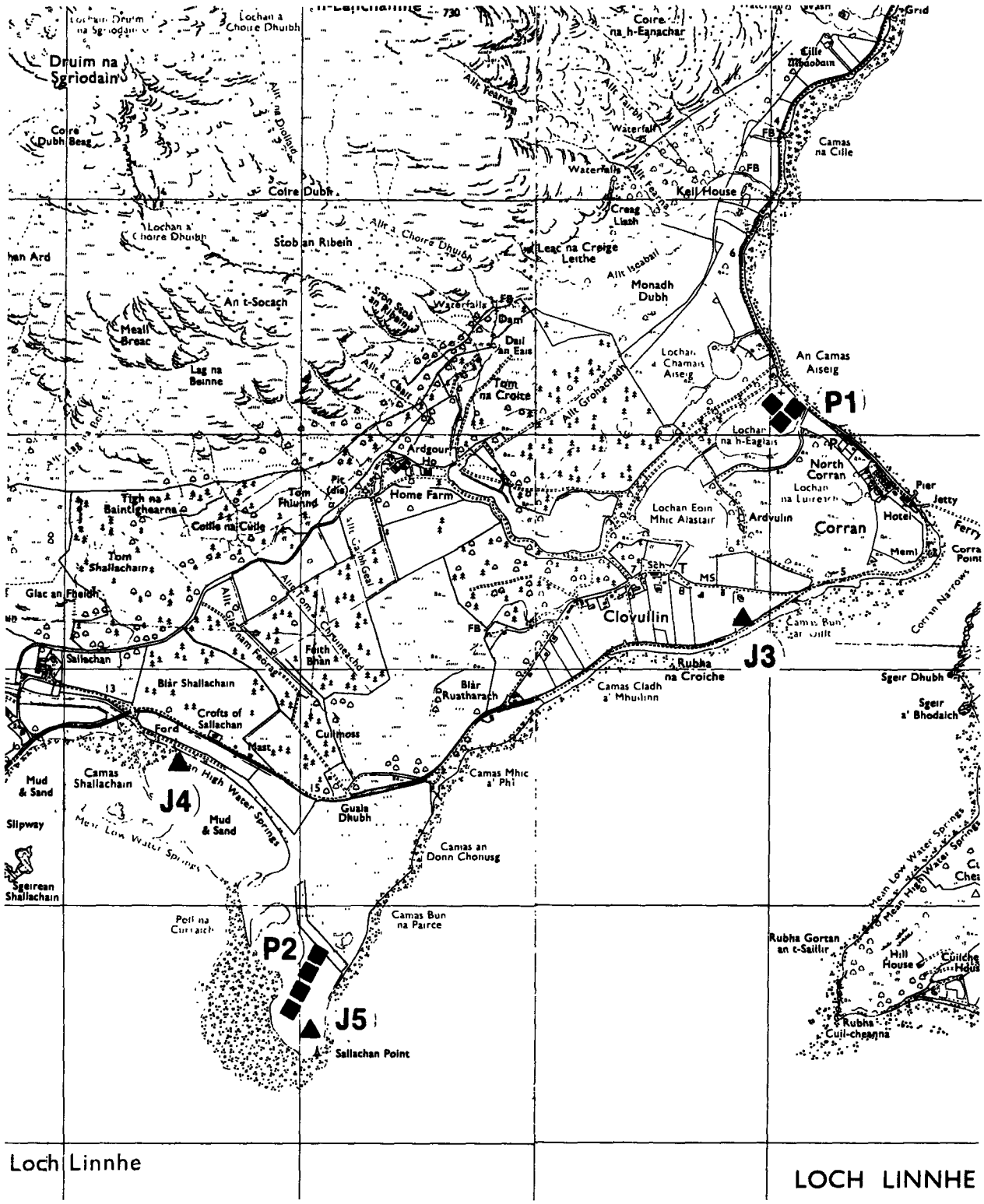

Figure 4. Lower-loch locations of J3, J4, J5, P1, and P2 at a scale of 1:25,000. Reproduced from the 1978 Ordnance Survey map with the permission of the Controller of Her Majesty's Stationery Office, © Copyright.

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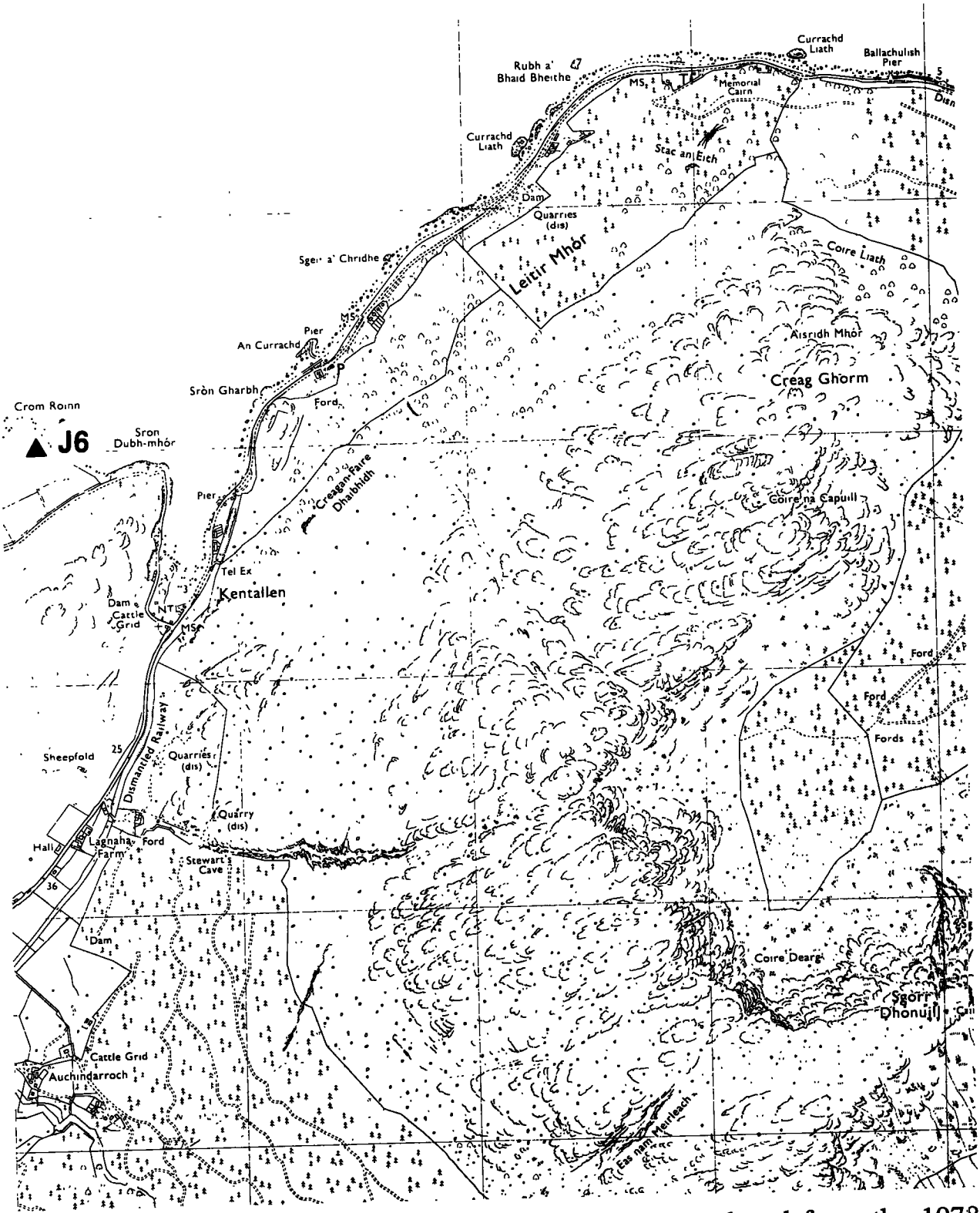

Figure 5. Location of J6 at a scale of 1:25,000. Reproduced from the 1978 Ordnance Survey map with the permission of the Controller of Her Majesty's Stationery Office, © Copyright.

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Table 5. Location of calibration sites

Site	Latitude, N		Longitude, W	
	degrees	minutes	degrees	minutes
J1	56	46.07	5	13.90
J2	56	46.47	5	9.90
J3	56	43.15	5	15.10
J4	56	42.90	5	17.50
J5	56	4207	5	16.90
J6	56	40.70	5	15.70
P1	56	43.53	5	15.20
P2	56	42.20	5	17.00

away. Similarly, the serial No. 3 PARCs were deployed some 50 meters away from the serial No. 2 pair. Serial No. 1 PARCs received H polarization and transmitted V polarization back to the radar. Serial No. 2 PARCs received 45-degree polarization and transmitted 45-degree polarization. Serial No. 3 PARCs received V polarization and transmitted H polarization. The old C-band PARC transmitted and received 135-degree polarization. Figure 6 shows the locations of the PARCs in detail; the transponder, P1, is shown in Figure 7.

Deployment Accuracy

The corner reflectors were deployed such that each reflector pointed at an angle perpendicular to the 39-degree flight path (i.e., the horizontal edge of the bottom panel was aligned with the aircraft flight track). The inclination of the boresight of the reflector with respect to the horizontal was around 45 degrees. Furthermore, the horizontal edge of the bottom panel was leveled. Table 6 shows the orientation of each reflector in these three categories: the first row tabulates the pointing angle of the horizontal edge of the bottom panel, the second row tabulates the inclination of the reflector at boresight with respect to the ground, and the third row tabulates the levelness of the reflectors. The inclination of the reflector was determined by the wooden supports beneath the front edge of the bottom panel; the wooden mounts provided an inclination of 43 degrees. The variation in inclination shown in the table was a result of the slope of the terrain. The corner reflectors are shown in Figures 8 through 13.

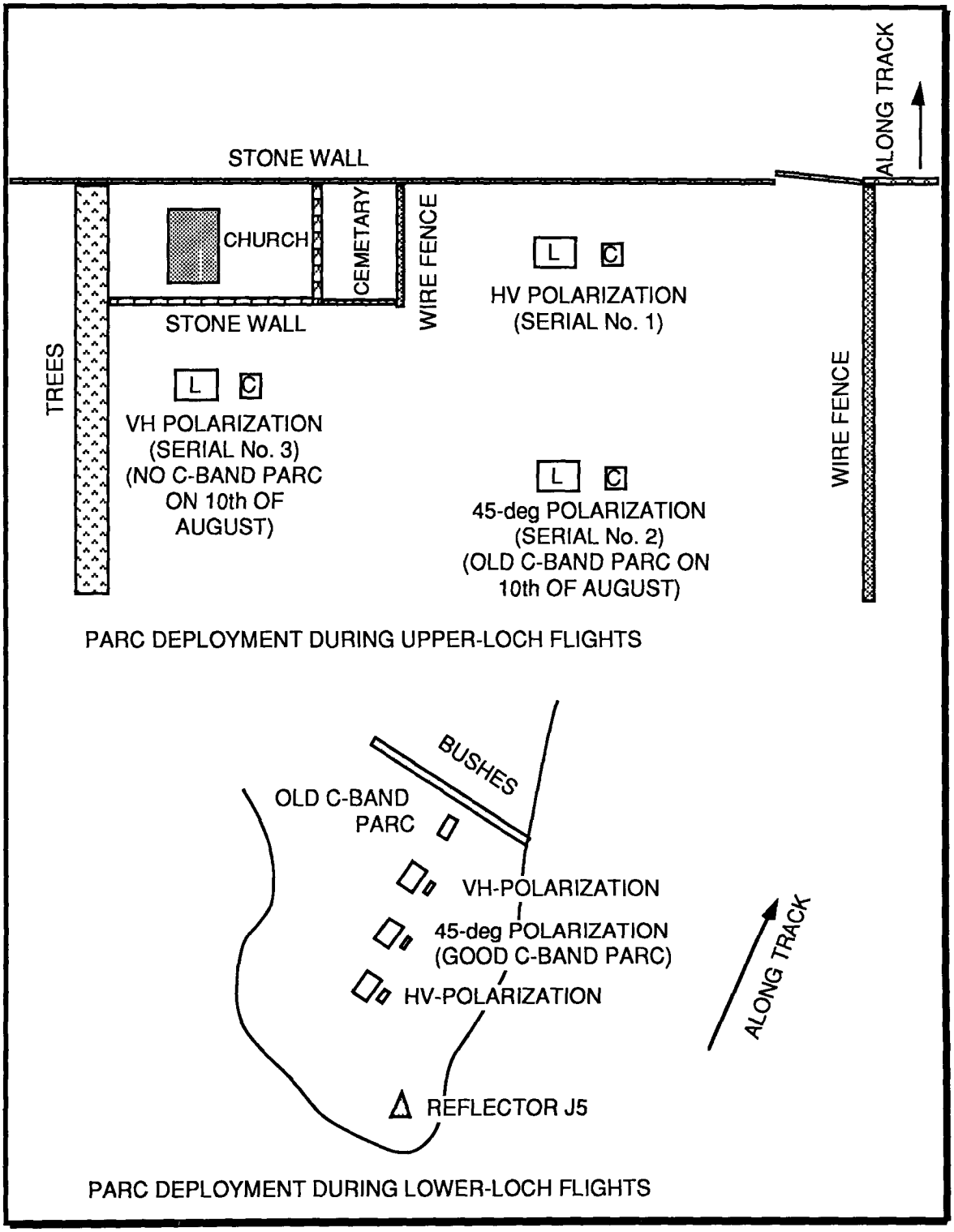

Figure 6. Location of the active transponders

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Figure 7. P1 site

Table 6. Deployment orientation for the corner reflectors

Parameter	Reflector					
	J1	J2	J3	J4	J5	J6
Heading, deg	39	39	39	38	39	39
Inclination, deg	41	45	45	43	44	44
Levelness, deg	0	0	0	2, CCW	0	0

On the second day of PARC deployment (August 10, 1989), two of the C-band PARCs did not function. The C-band PARCs have two amplifiers; the power supplies of the dc bias to one of the amplifiers failed on these two PARCs. It was decided to deploy the remaining good C-band HV-polarized PARC and the old 135-degree-polarized PARC, only. During the lower-loch experiment, all the PARCs, including the two failing C-band PARCs and the old 135-degree-polarized PARC, were deployed.

Preliminary Observations

A few images of both the upper Loch Linnhe runs and the lower Loch Linnhe runs were processed, and corner reflectors J1 through J5 were identified. Reflector J6 was too close to nadir; it might show up in the 55-degree incidence-angle runs, but this remains to be verified. In these same images, it was also verified that the PARCs are visible in the imagery in accordance with theoretical expectation. That is,

(1) Only the 45-degree-polarized PARCs (SN2) were visible in the HH- and VV-polarized images.

(2) Only the HV-polarized (SN3) and the 45-degree-polarized PARCs were visible in the HV images.

(3) Only the VH-polarized (SN1) and the 45-degree-polarized PARCs were visible in the VH images.

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Figure 8. J1 site

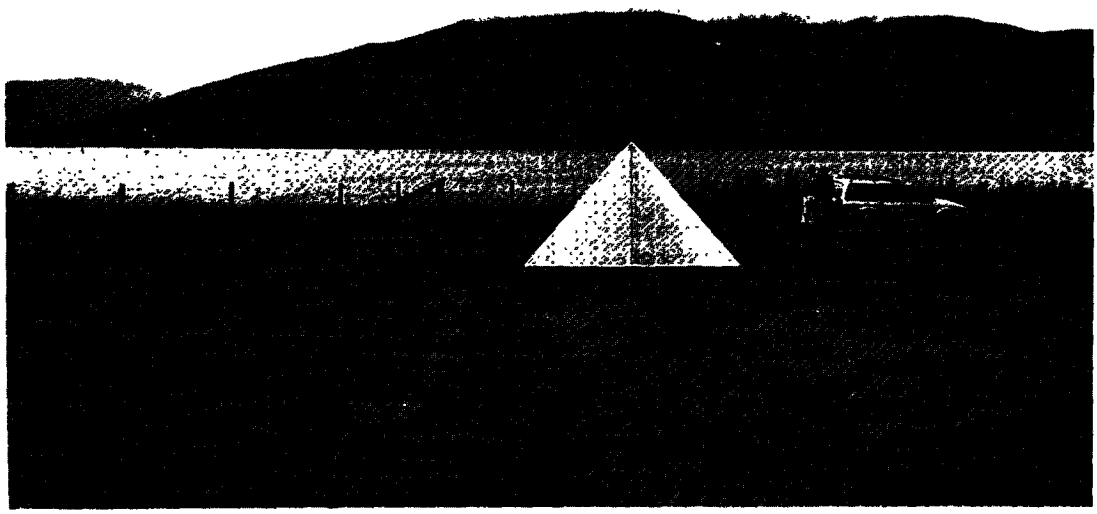

Figure 9. J2 site

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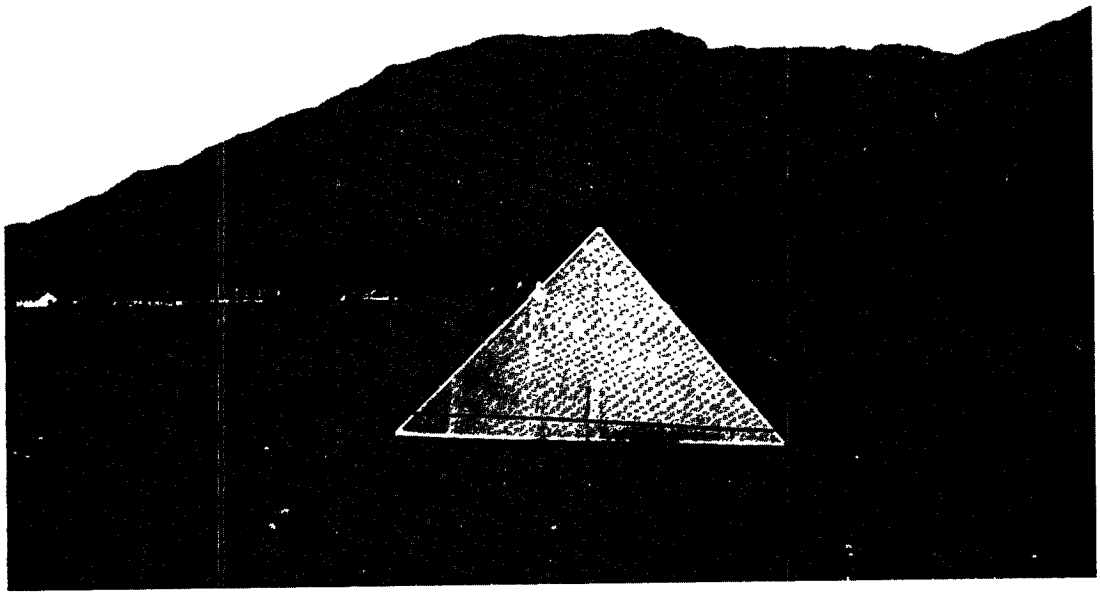

Figure 10. J3 site

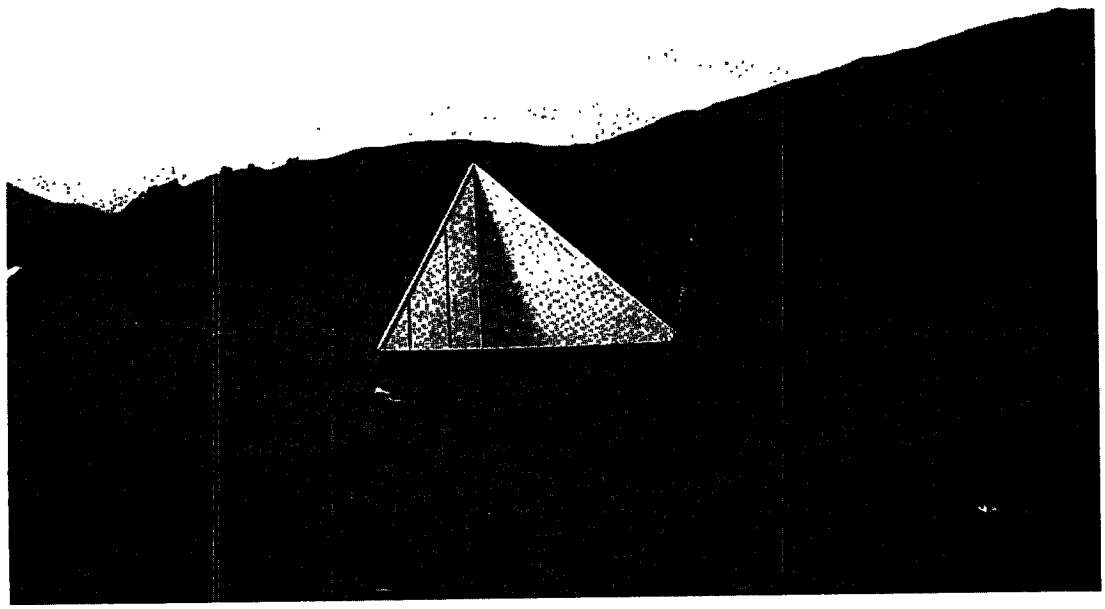

Figure 11. J4 site

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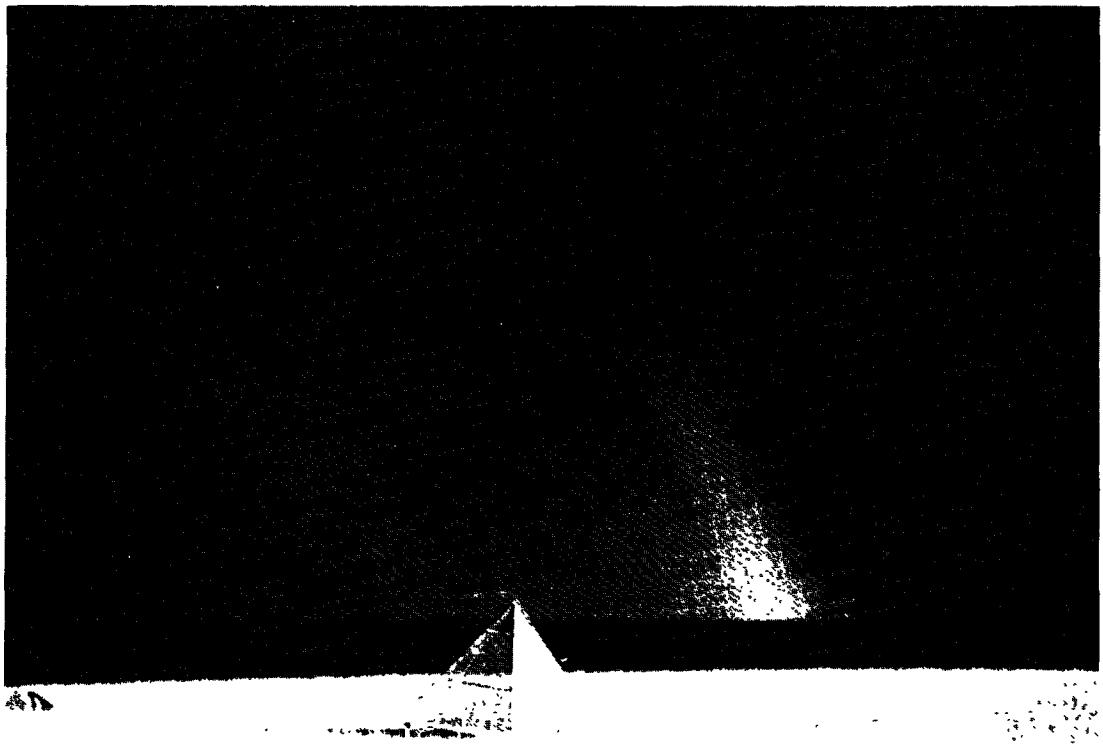

Figure 12. J5 site

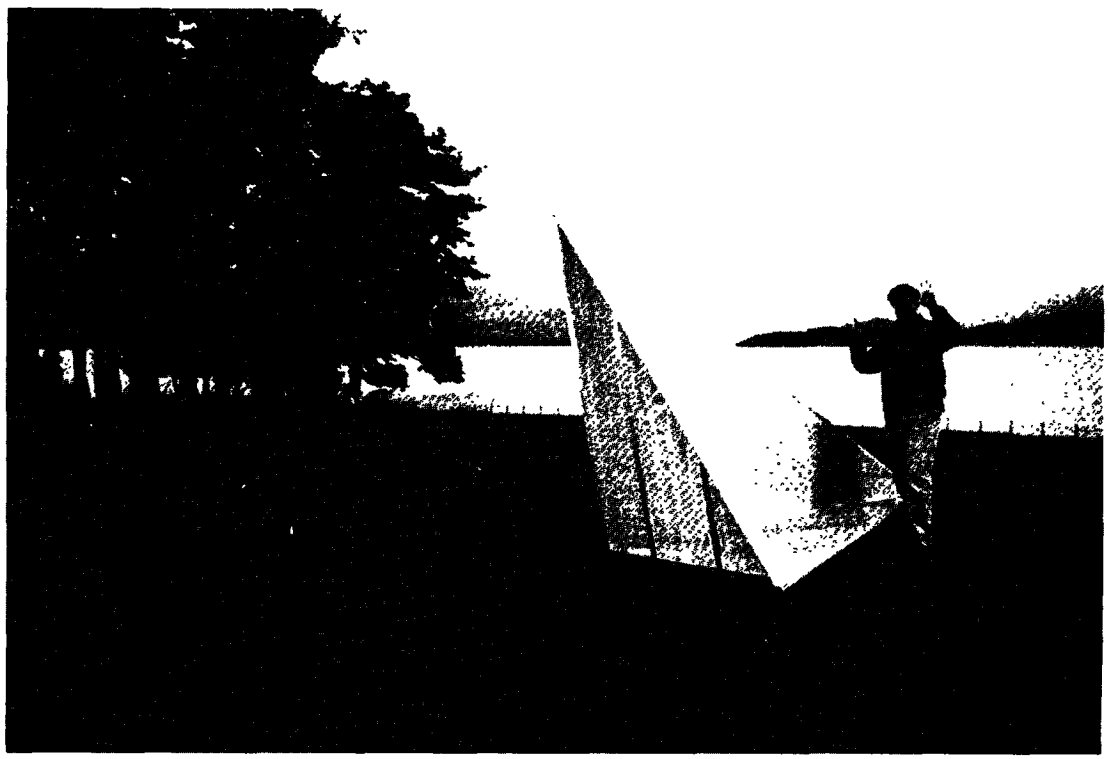

Figure 13. J6 site

Summary

The data collected at Loch Linnhe form an extensive set of external calibration data. There are 12 runs along the same track every day for 4 days at the upper and lower lochs, respectively. The runs were flown at 25-, 40-, and 55-degree incidence angles. This data set should allow us to compare the L-band calibration accuracies between the corner reflectors and the PARCs, and can be used to calibrate the phase and amplitude of the image pixels.

Reference

1. Y. Lou, "External Calibration Plan for 1989 Loch Linnhe Experiment—Version 1.0," JPL Interoffice Memorandum 3340-89-127, May 1989 (JPL internal document).

Appendix

The Quick-Look Radar Images

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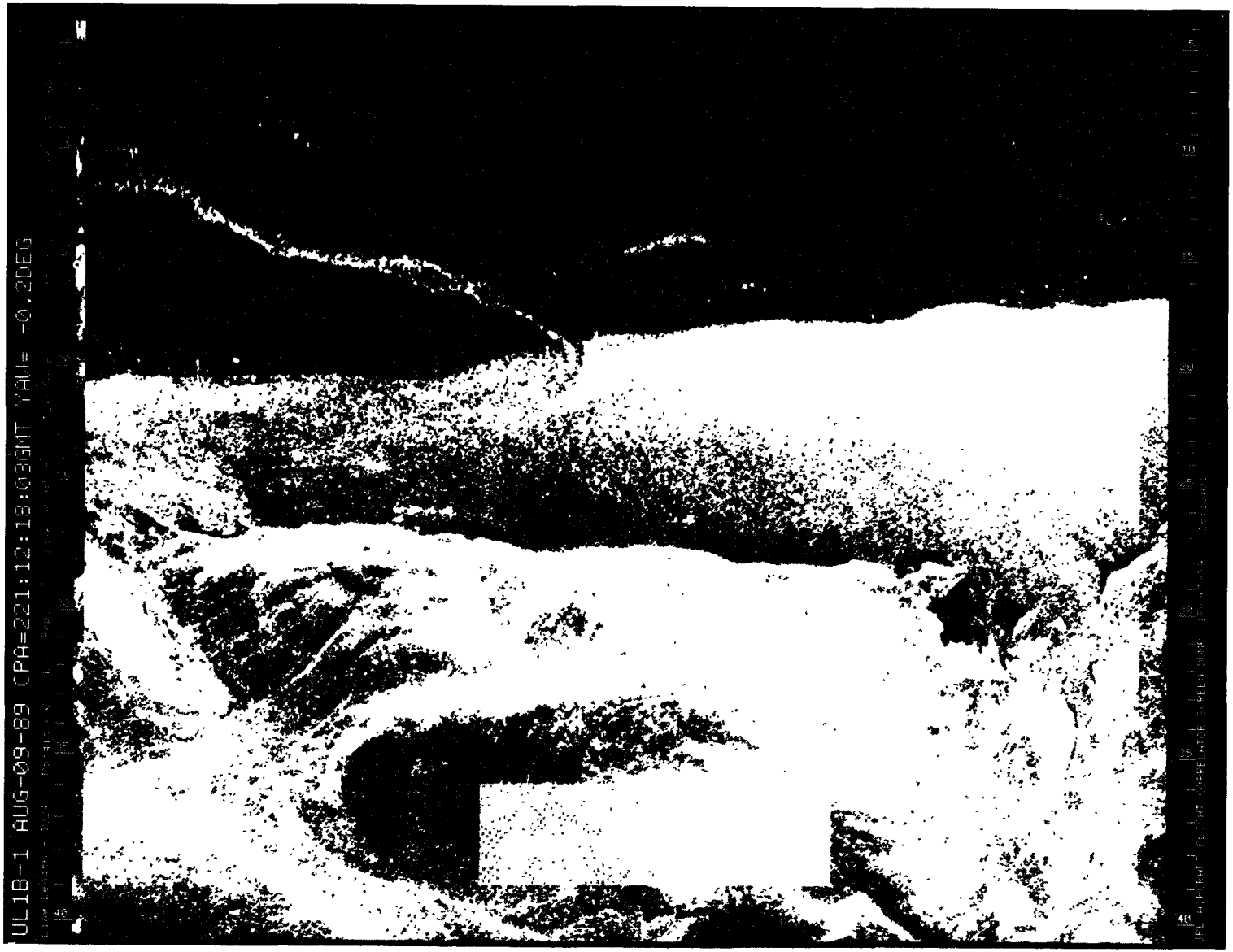

Figure A-1. August 9, 1989, Pass 1, CPA 221:12:18:03GMT CVV

Figure A-2. August 9, 1989, Pass 2, CPA 221:12:39:48GMT LVV

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Figure A-3. August 9, 1989, Pass 3, CPA 221:12:59:56GMT PVV

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Figure A-4. August 9, 1989, Pass 4, CPA 221:13:20:05GMT CHH

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Figure A-5. August 9, 1989, Pass 5, CPA 221:13:40:08GMT LHH

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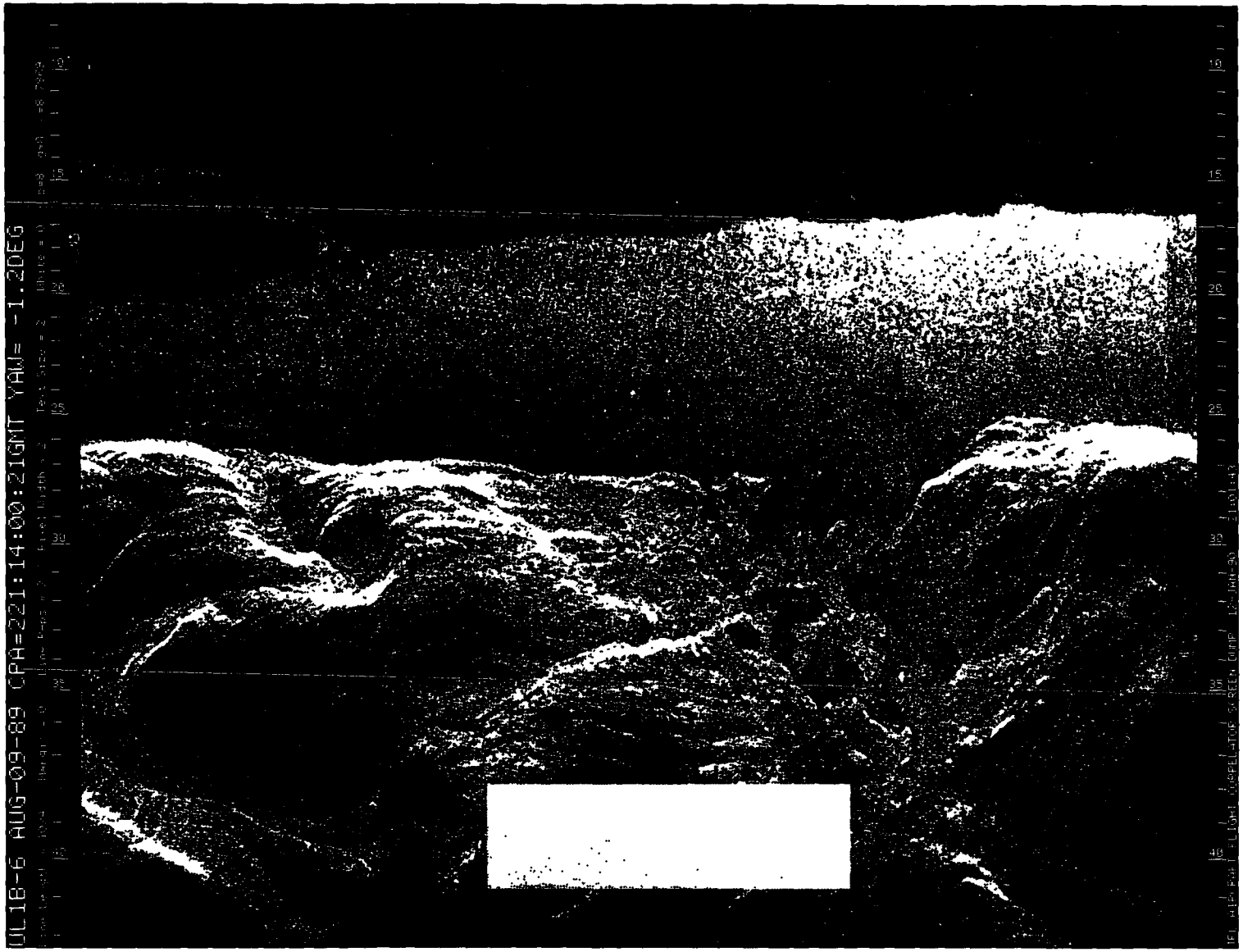

Figure A-6. August 9, 1989, Pass 6, CPA 221:14:00:21GMT CVV

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Figure A-7. August 9, 1989, Pass 7, CPA 221:14:20:00GMT CVV

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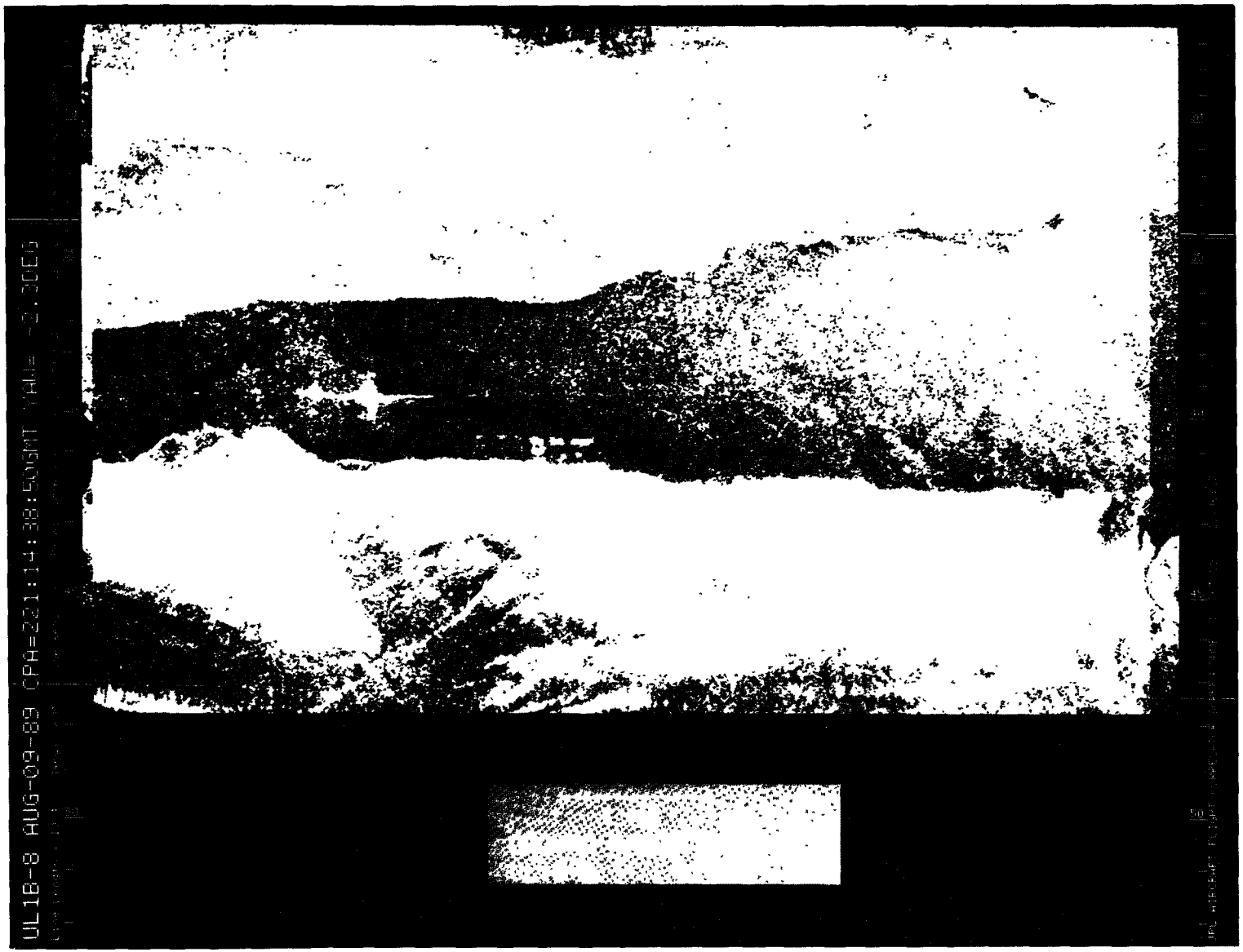

Figure A-8. August 9, 1989, Pass 8, CPA 221:14:38:50GMT CVV

Figure A-9. August 9, 1989, Pass 9, CPA 221:14:50:58GMT PVV

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Figure A-10. August 9, 1989, Pass 10, CPA 221:15:19:46GMT PVV

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Figure A-11. August 9, 1989, Pass 11, CPA 221:15:34:43GMT PVV

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Figure A-12. August 9, 1989, Pass 12, CPA 221:16:00:00GMT PVV

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Figure A-13. August 10, 1989, Pass 1, CPA 222:13:30:00GMT CVV

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Figure A-14. August 10, 1989, Pass 2, CPA 222:13:50:25GMT CVV

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Figure A-15. August 10, 1989, Pass 3, CPA 222:14:10:24GMT PVV

Figure A-16. August 10, 1989, Pass 4, CPA 222:14:30:07GMT PVV

Figure A-17. August 10, 1989, Pass 4, CPA 222:14:30:07GMT PHH

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Figure A-18. August 10, 1989, Pass 4, CPA 222:14:30:07GMT LVV

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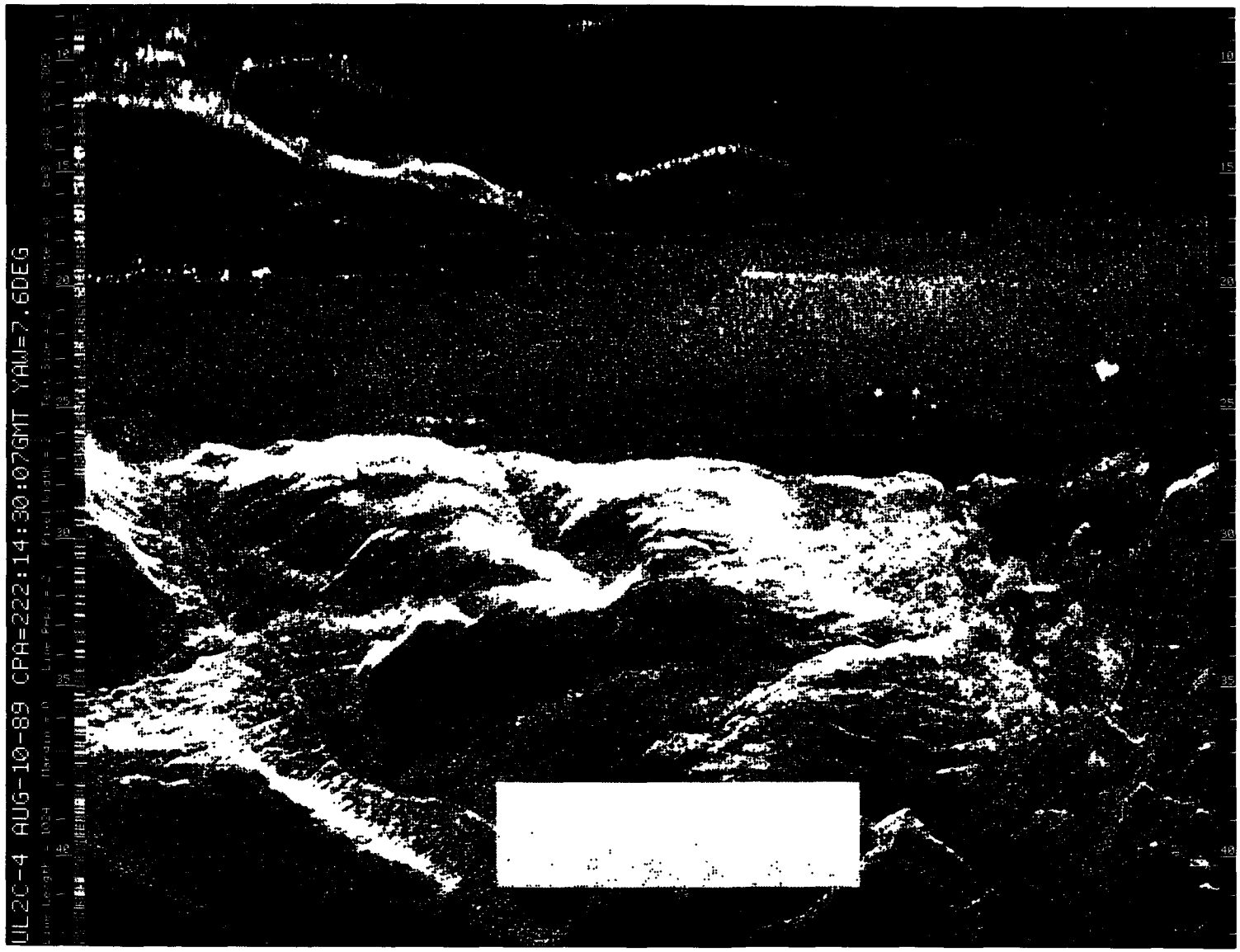

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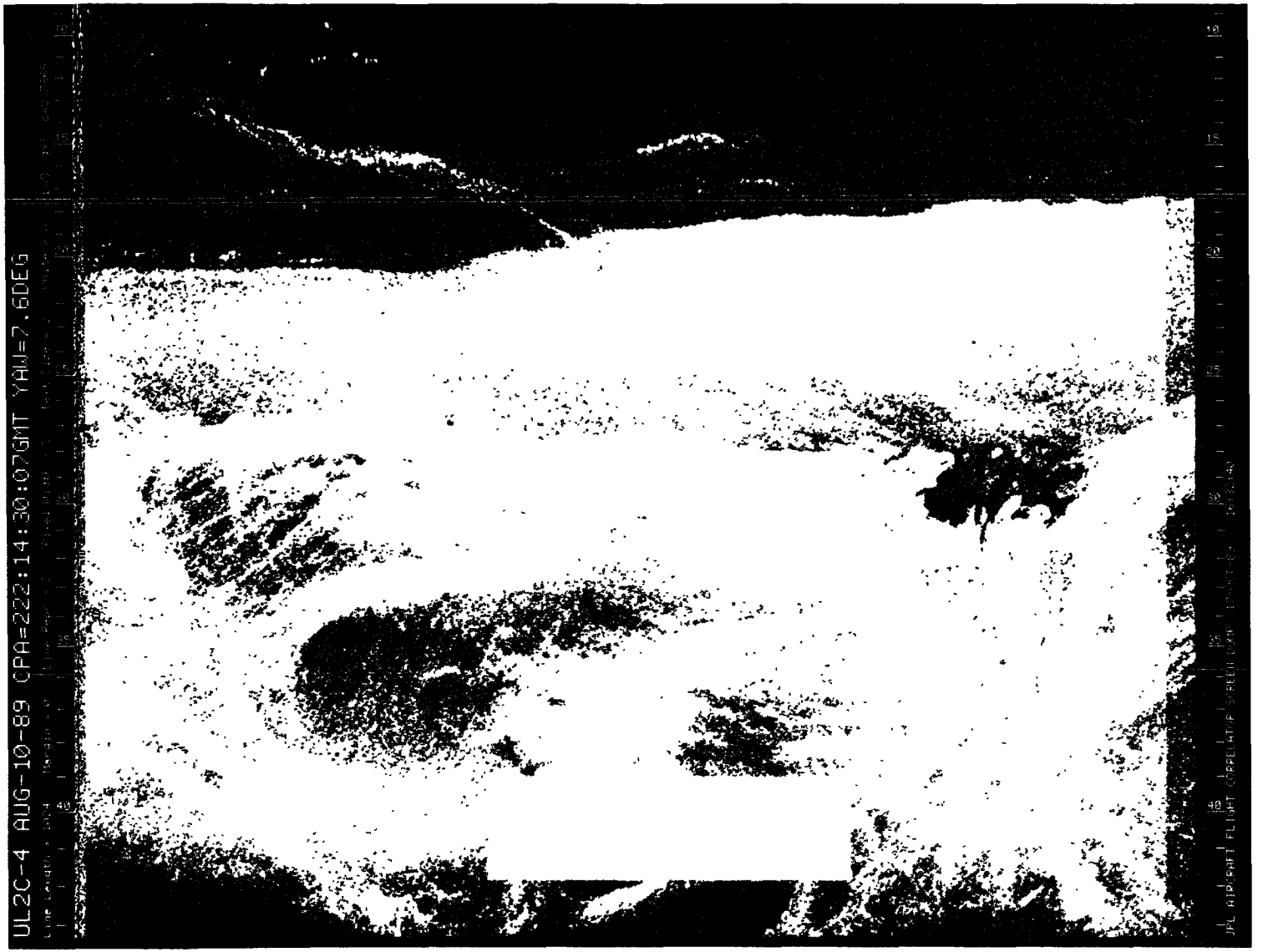

Figure A-20. August 10, 1989, Pass 4, CPA 222:14:30:07GMT CVV

Figure A-21. August 10, 1989, Pass 4, CPA 222:14:30:07GMT CHH

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Figure A-22. August 10, 1989, Pass 5, CPA 222:14:50:13GMT PVV

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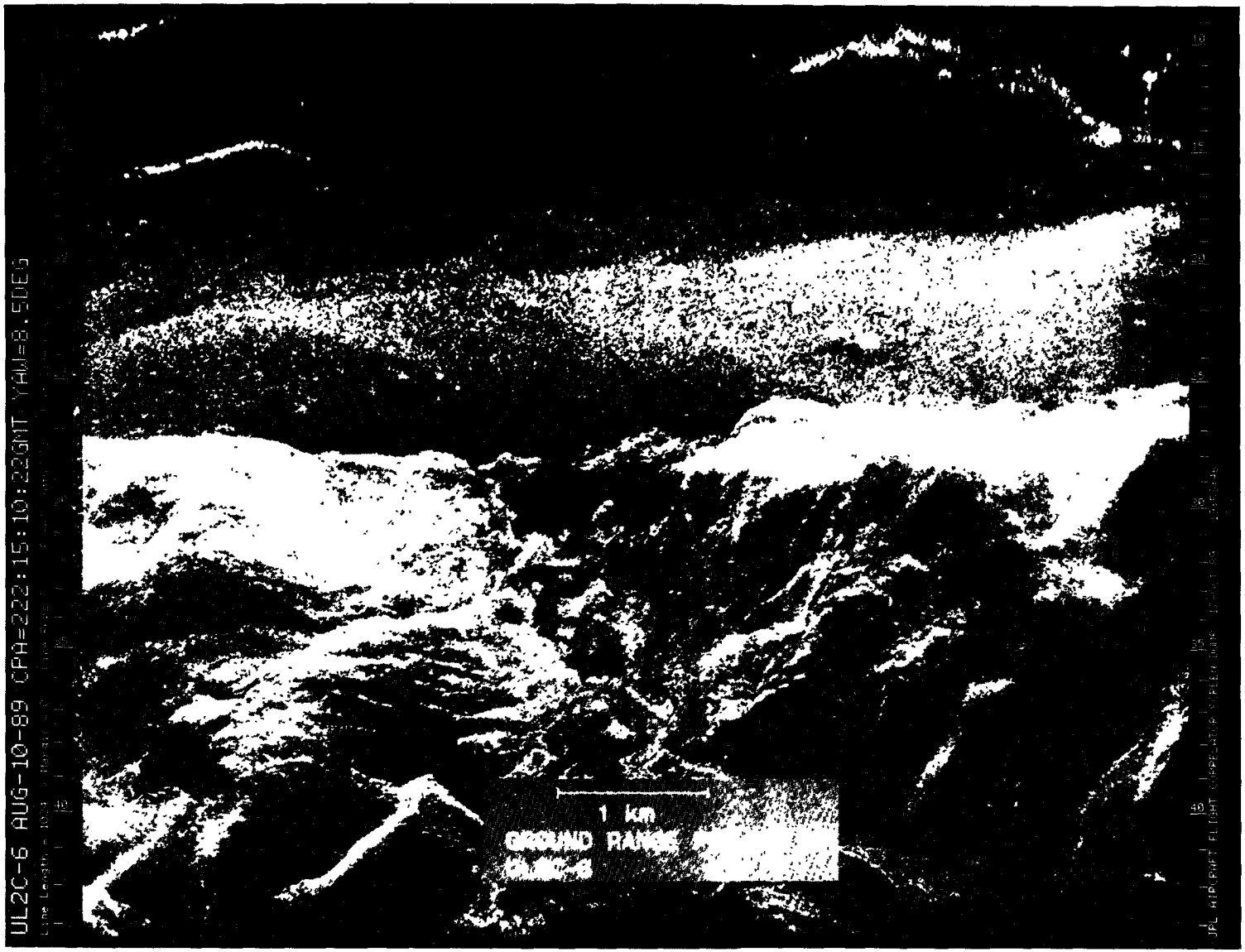

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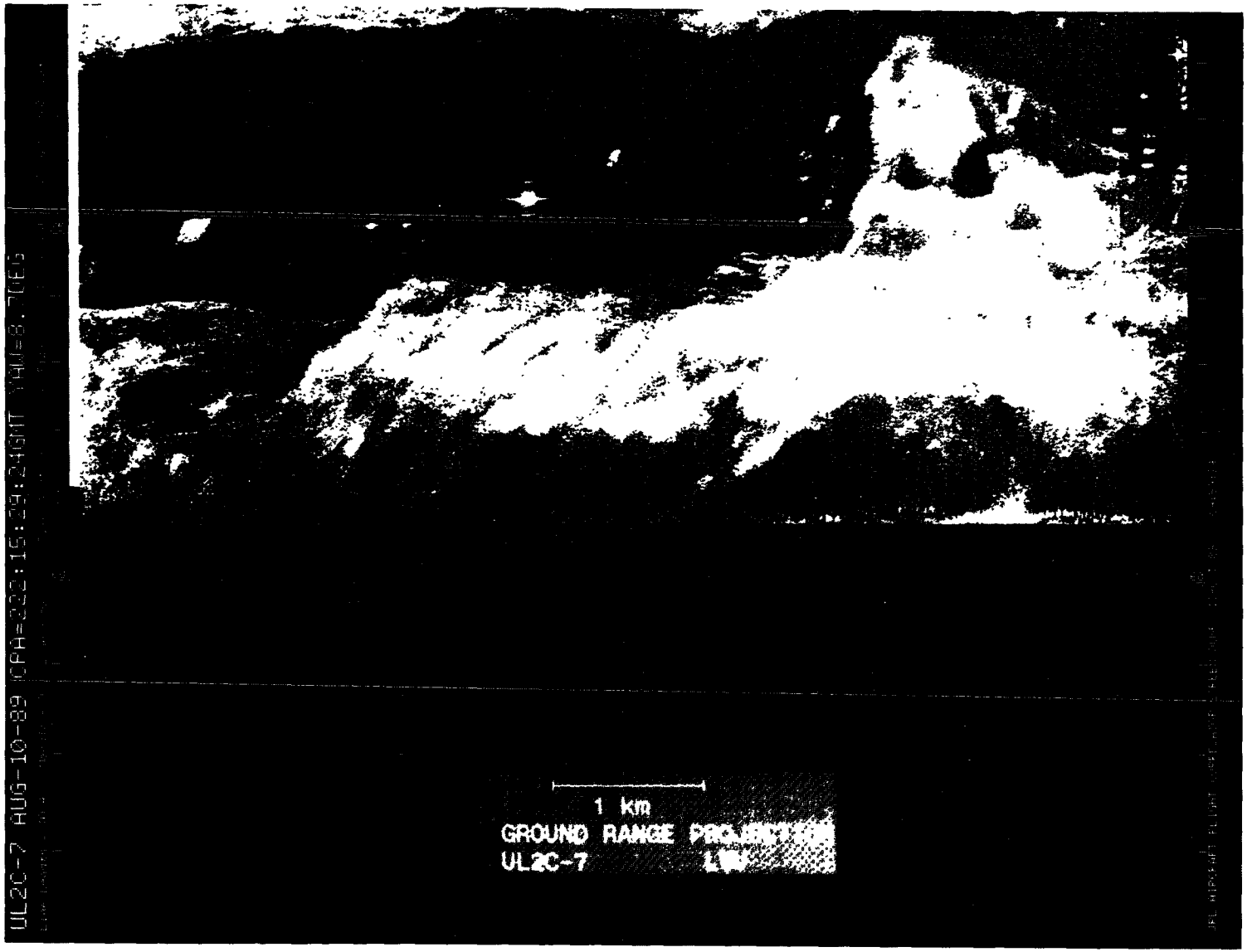


Figure A-24. August 10, 1989, Pass 7, CPA 222:15:29:24GMT LVV

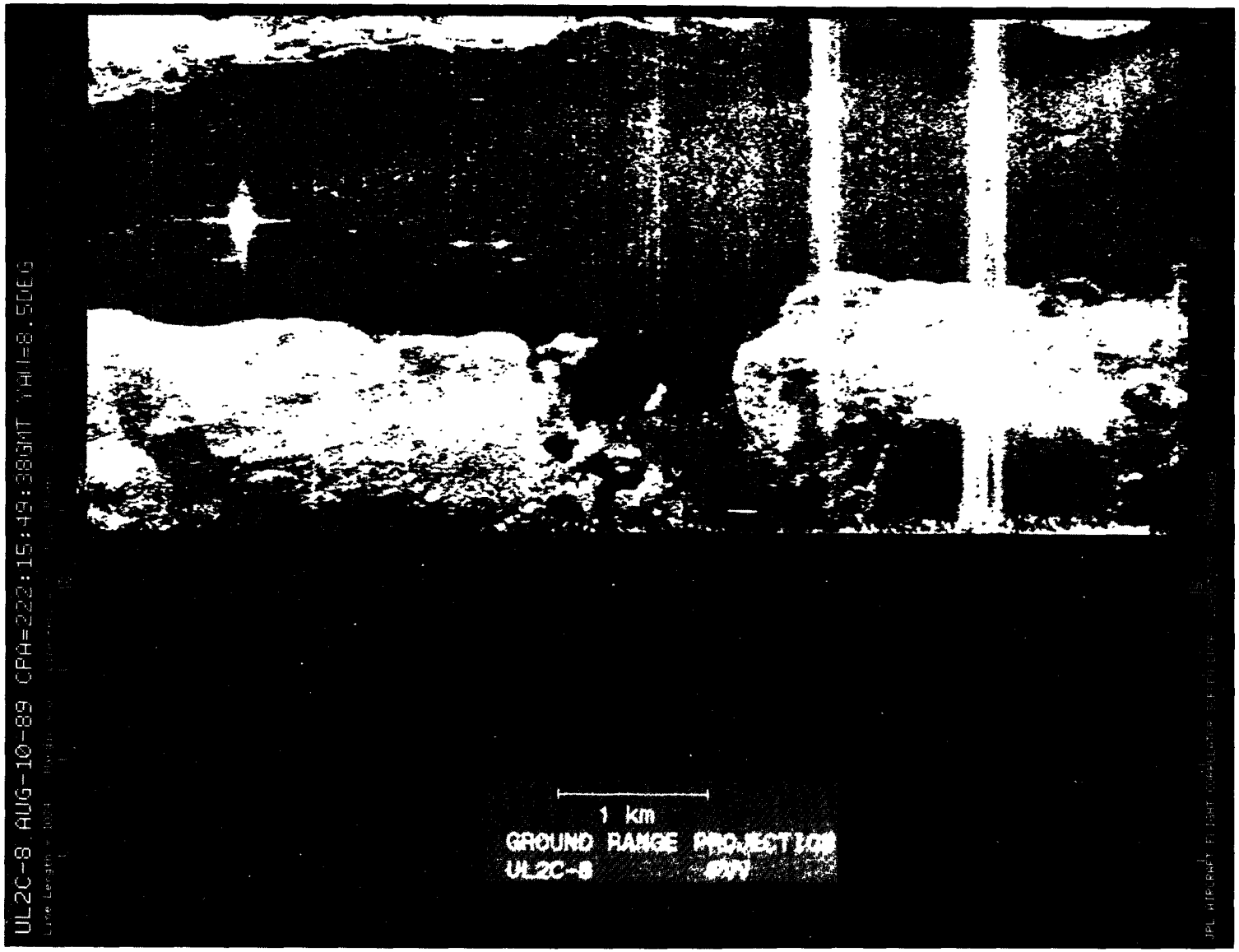


Figure A-25. August 10, 1989, Pass 8, CPA 222:15:49:38GMT PVV

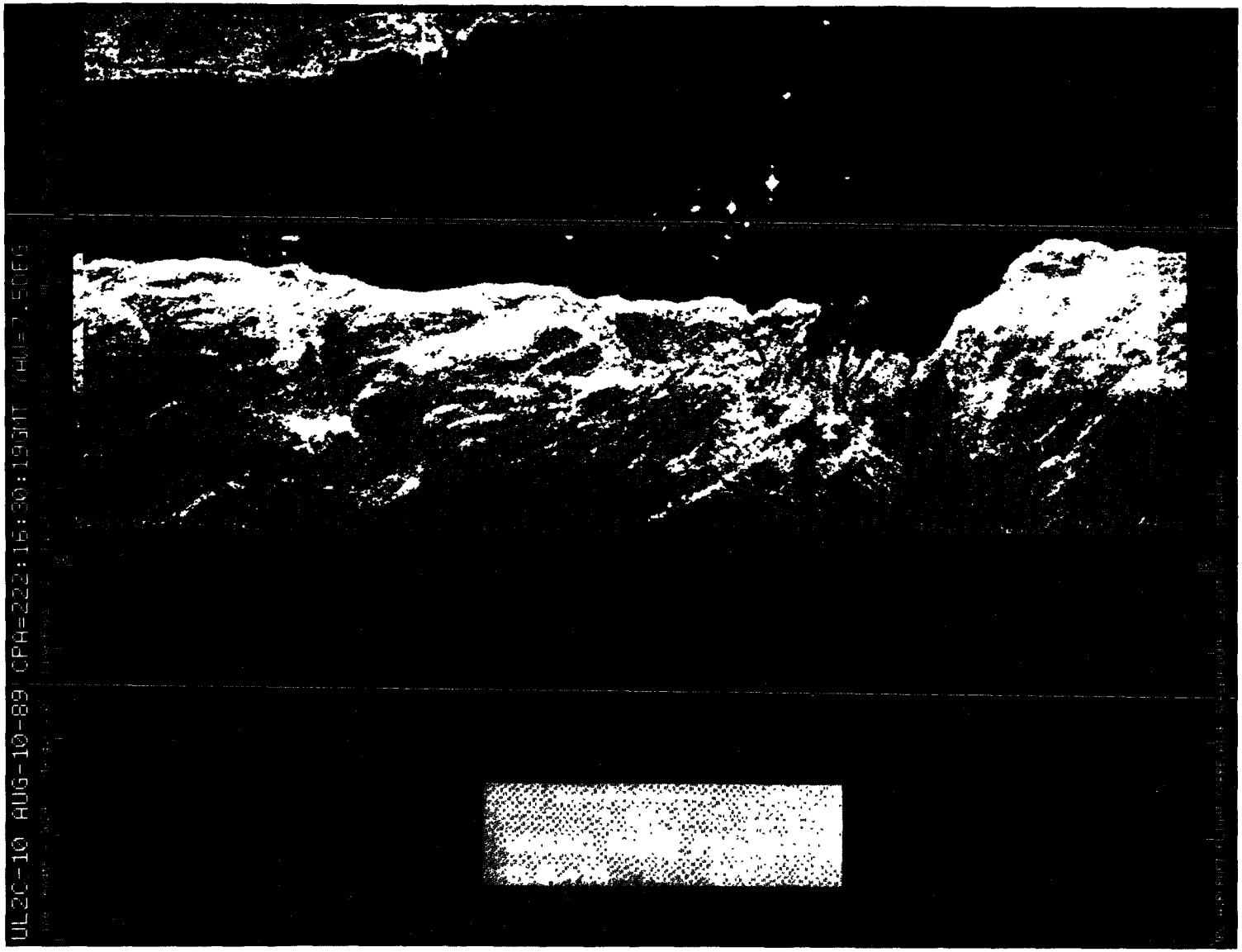
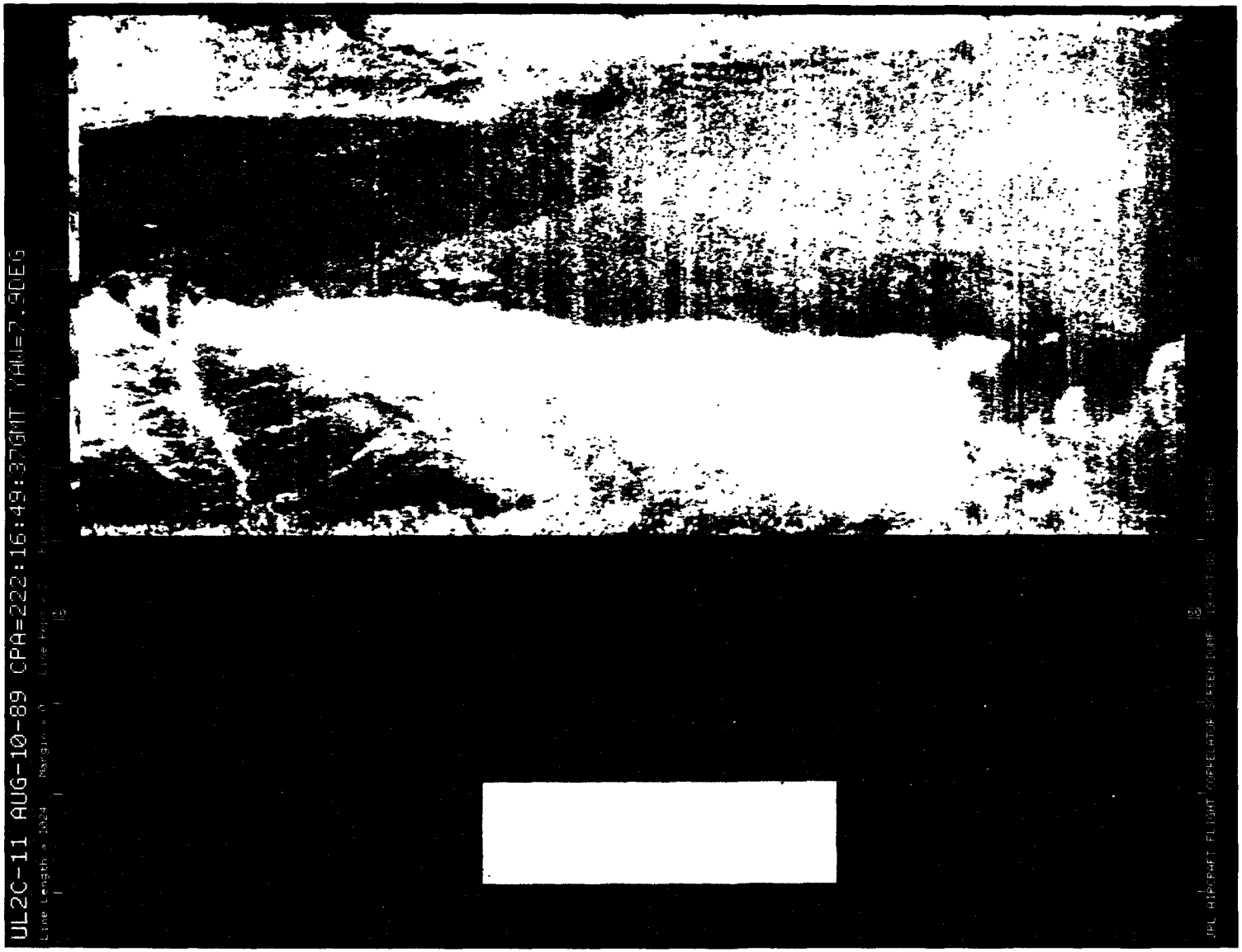


Figure A-26. August 10, 1989, Pass 10, CPA 222:16:30:19GMT CVV



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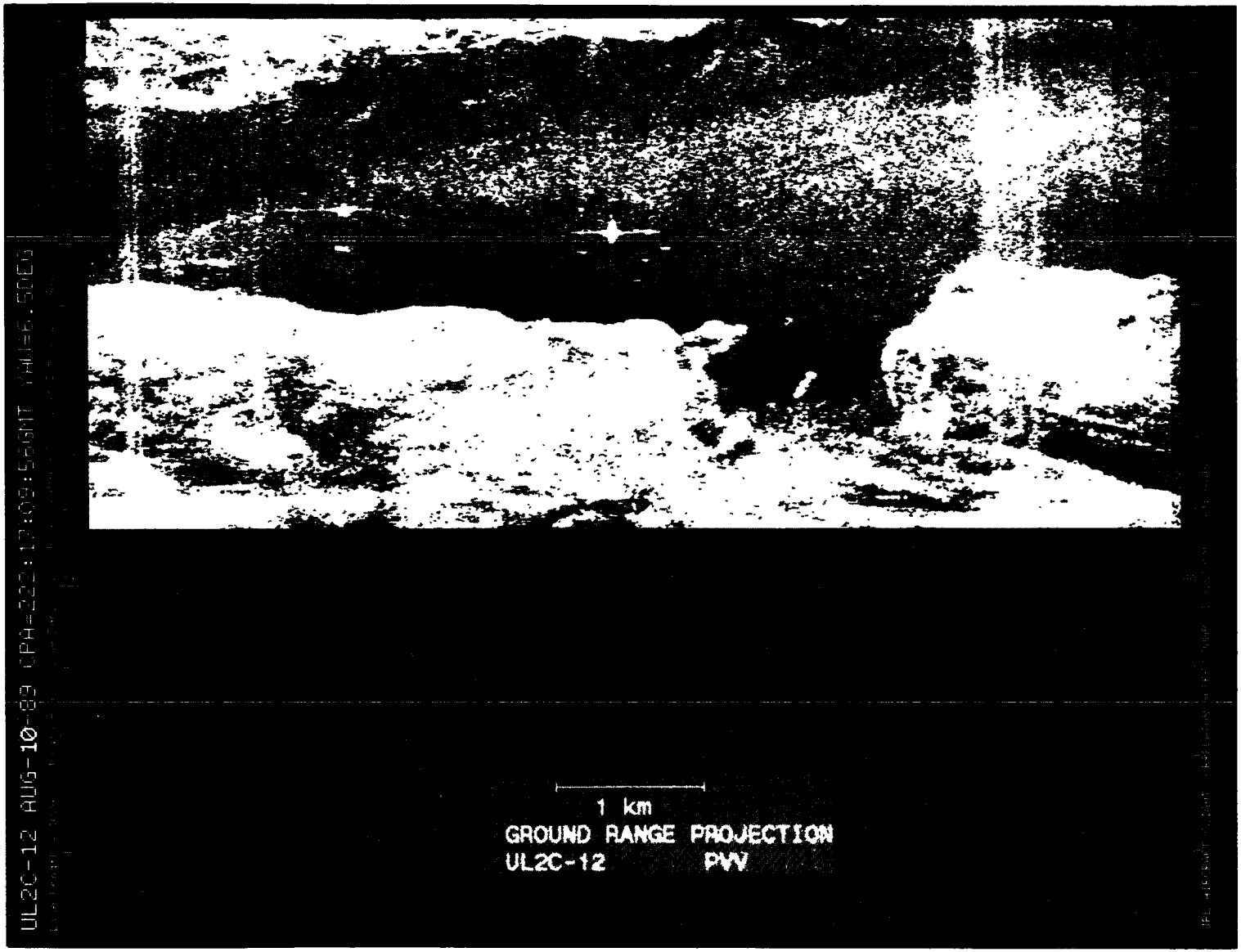


Figure A-28. August 10, 1989, Pass 12, CPA 222:17:09:56 GMT PVV

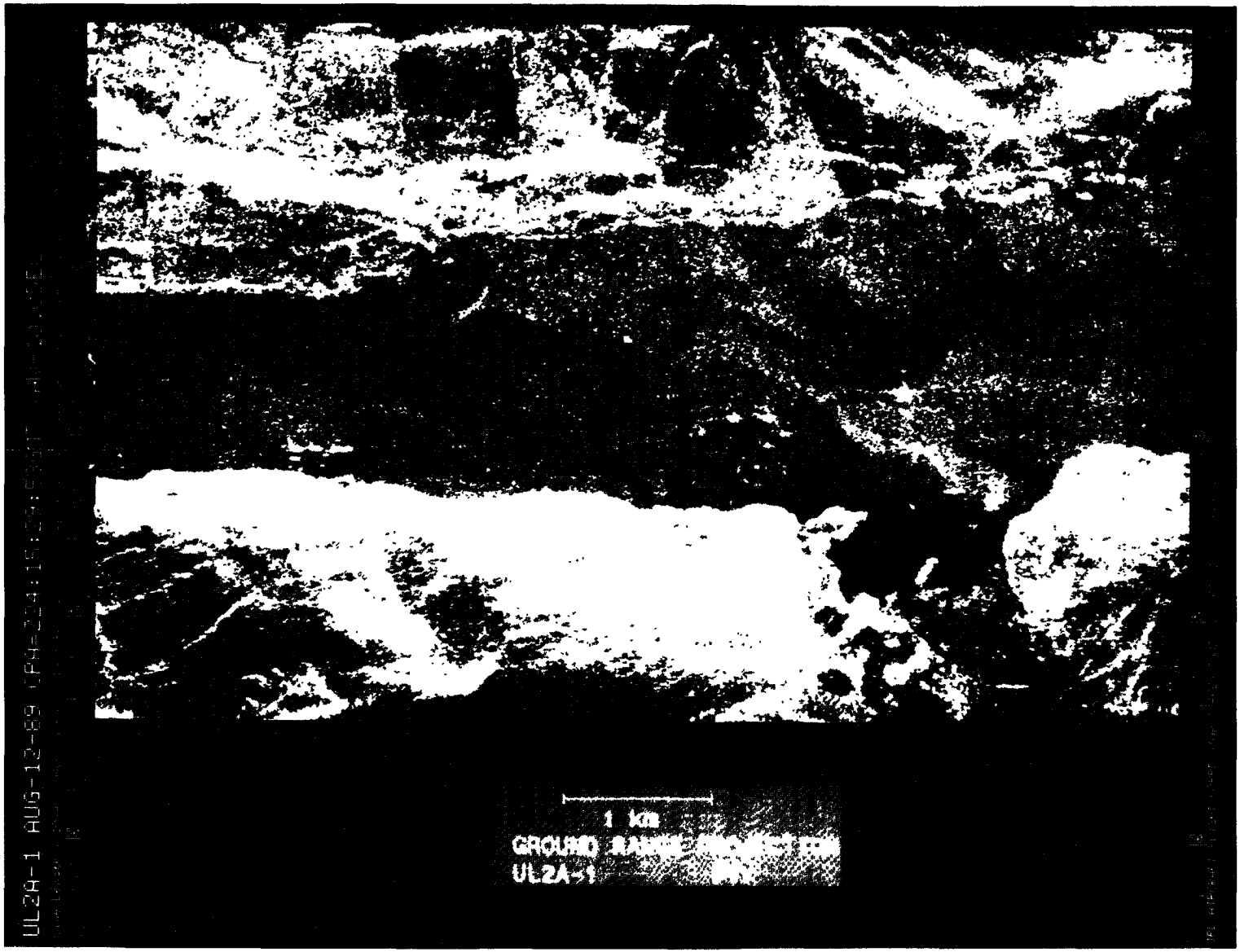
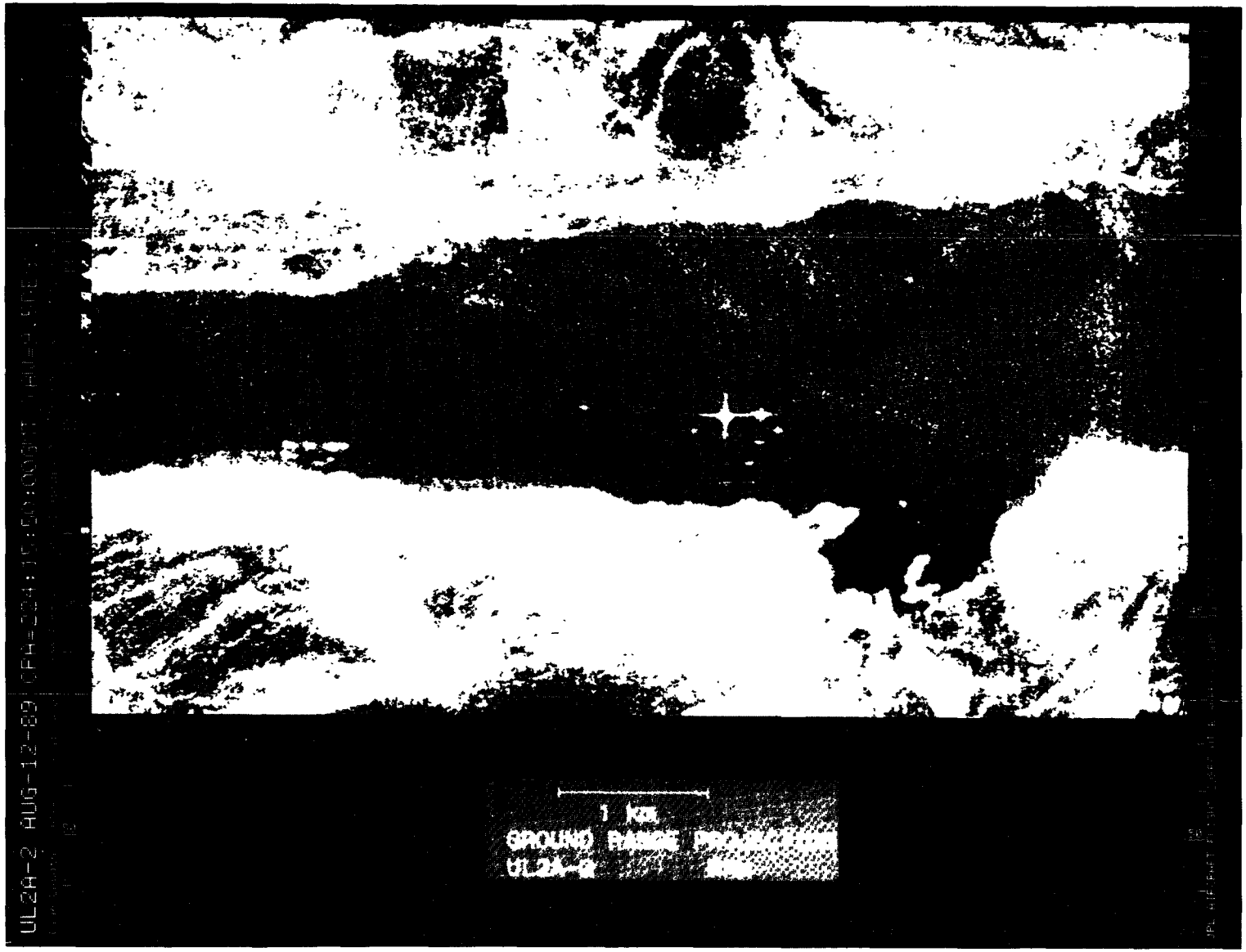


Figure A-29. August 12, 1989, Pass 1, CPA 224:15:29:53 GMT PVV



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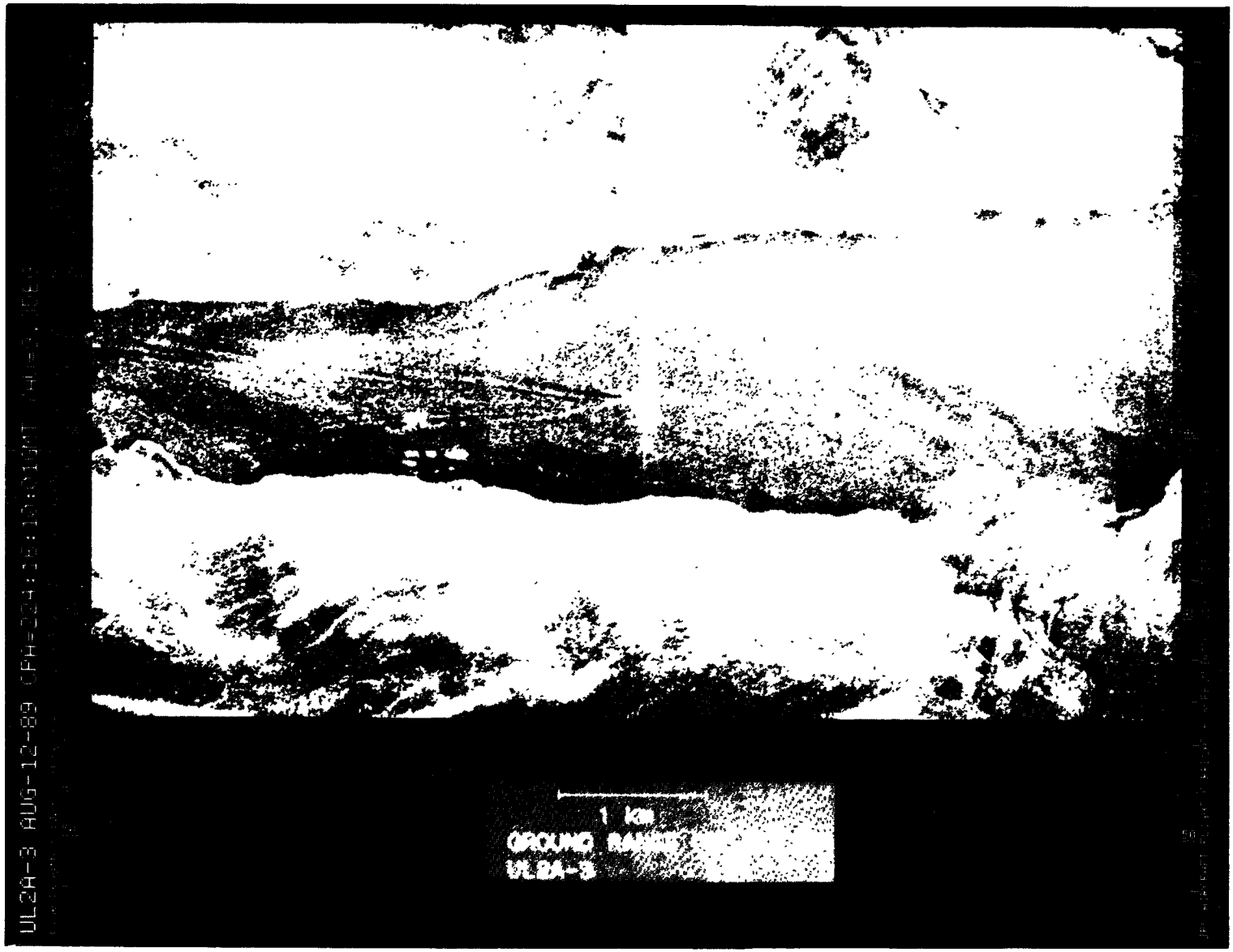

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Figure A-32. August 12, 1989, Pass 4, CPA 224:13:30:01GMT LHH

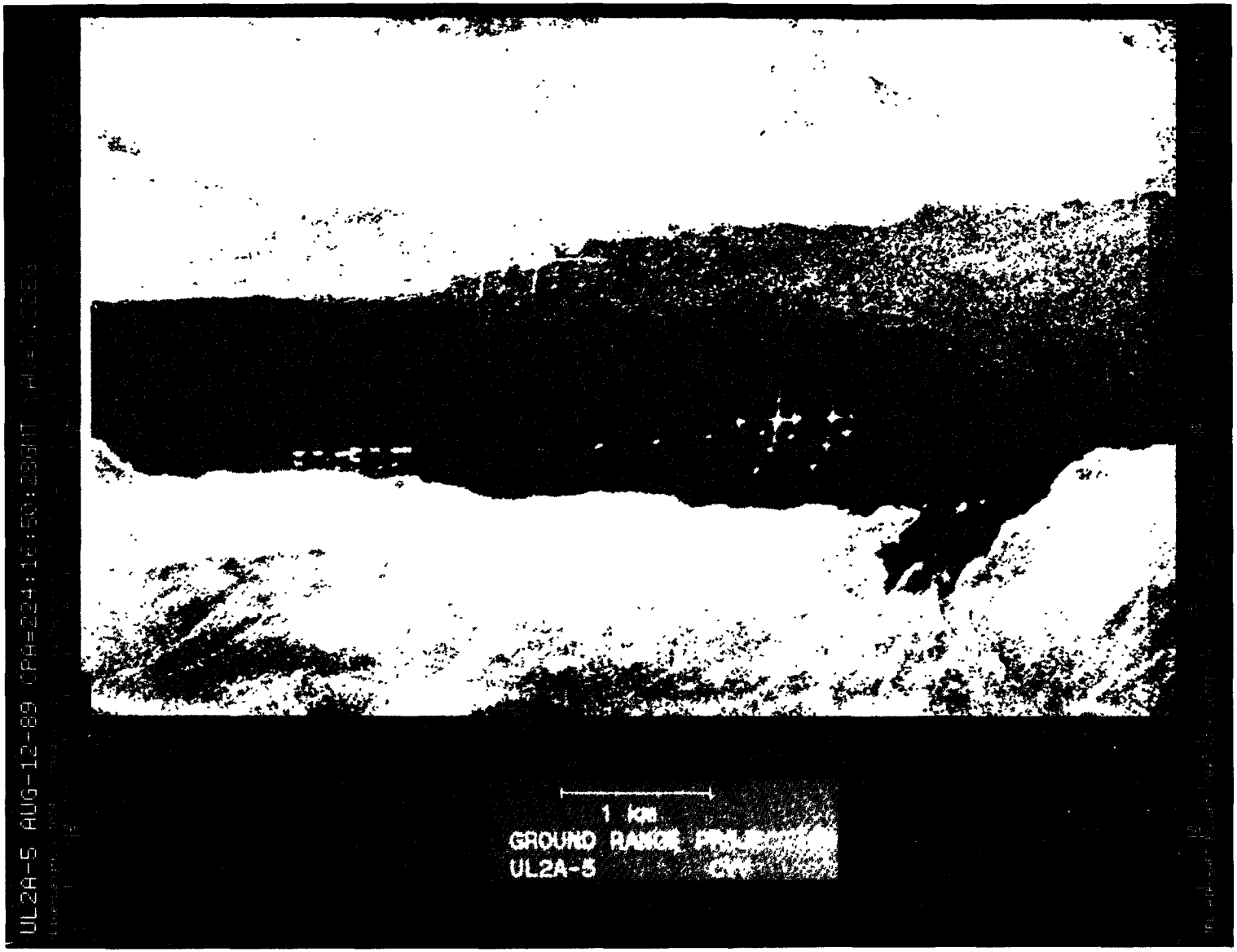

Figure A-33. August 12, 1989, Pass 5, CPA 224:16:50:28GMT CVV

Figure A-34. August 12, 1989, Pass 6, CPA 224:17:10:01GMT CHH

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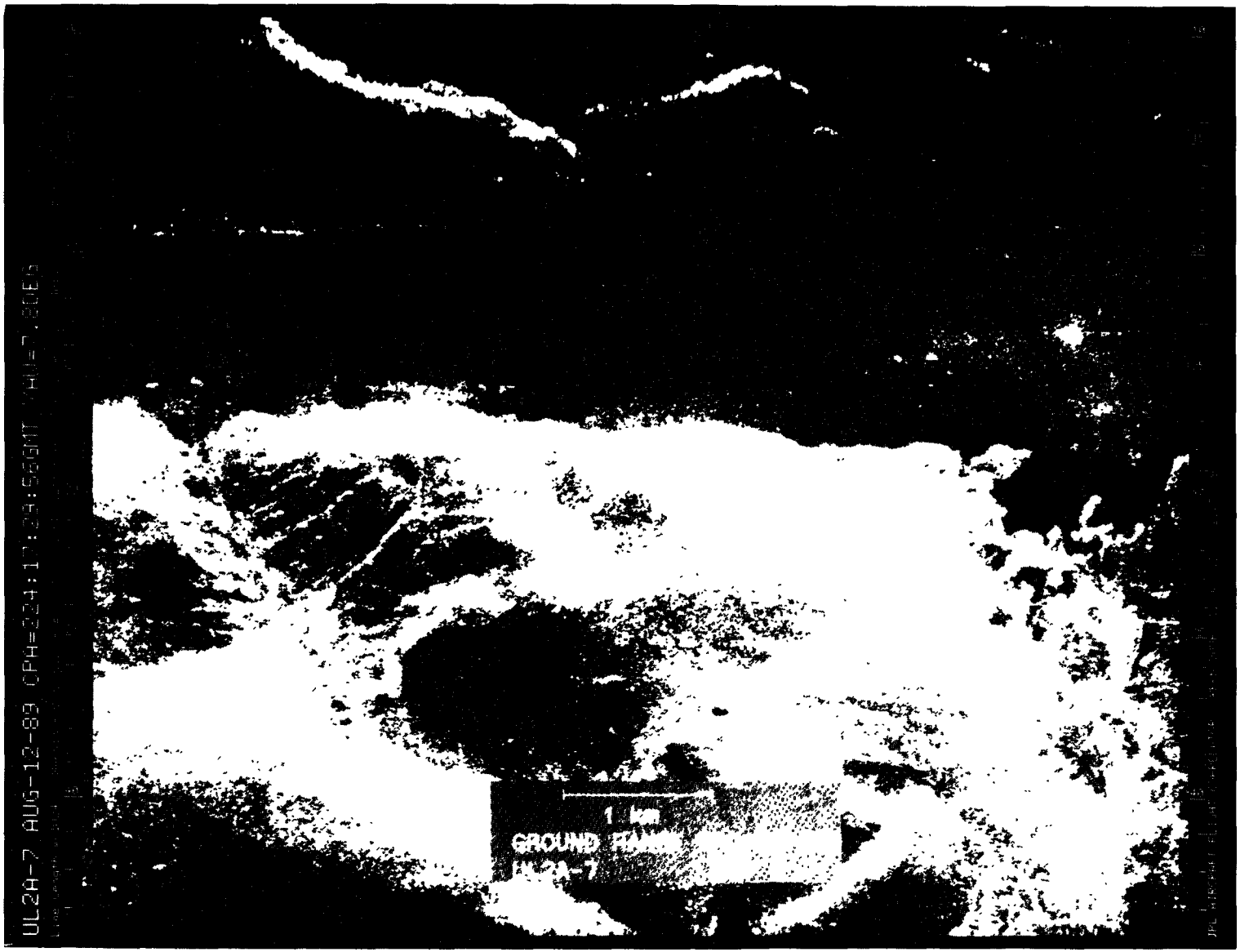

Figure A-35. August 12, 1989, Pass 7, CPA 224:17:29:56GMT PVV

Figure A-35 (Cont'd). August 12, 1989, Pass 7, CPA 224:17:29:56GMT PVV

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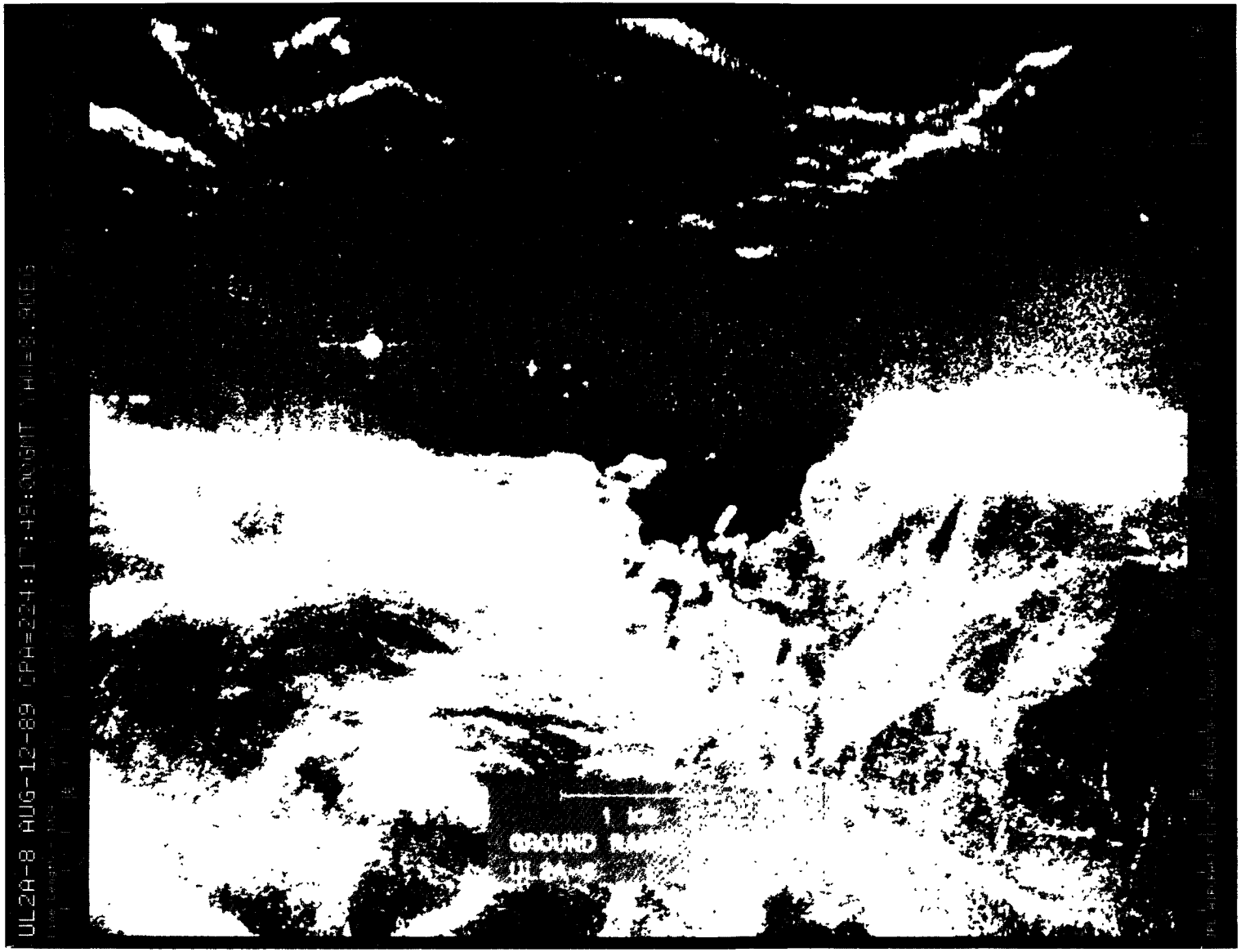

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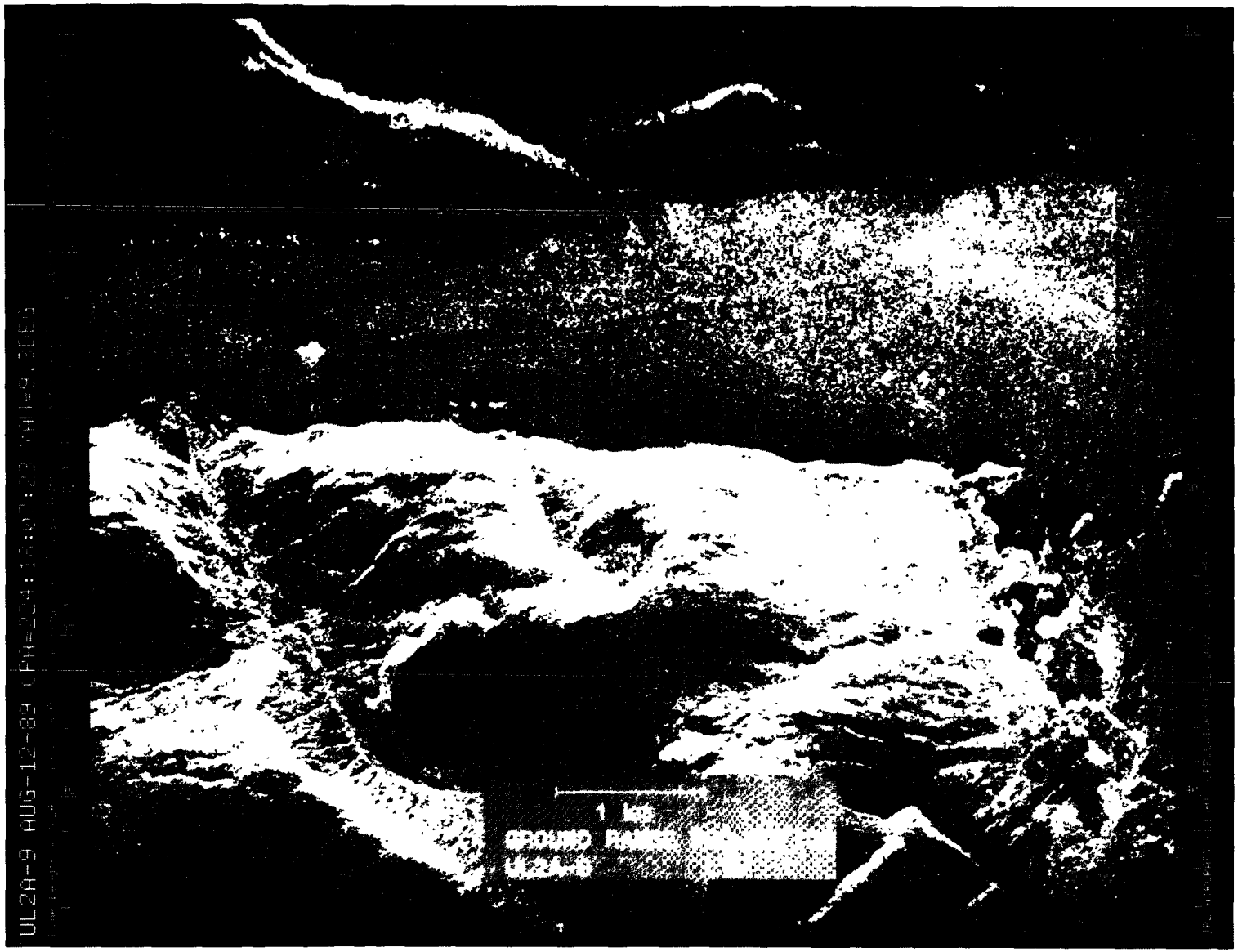

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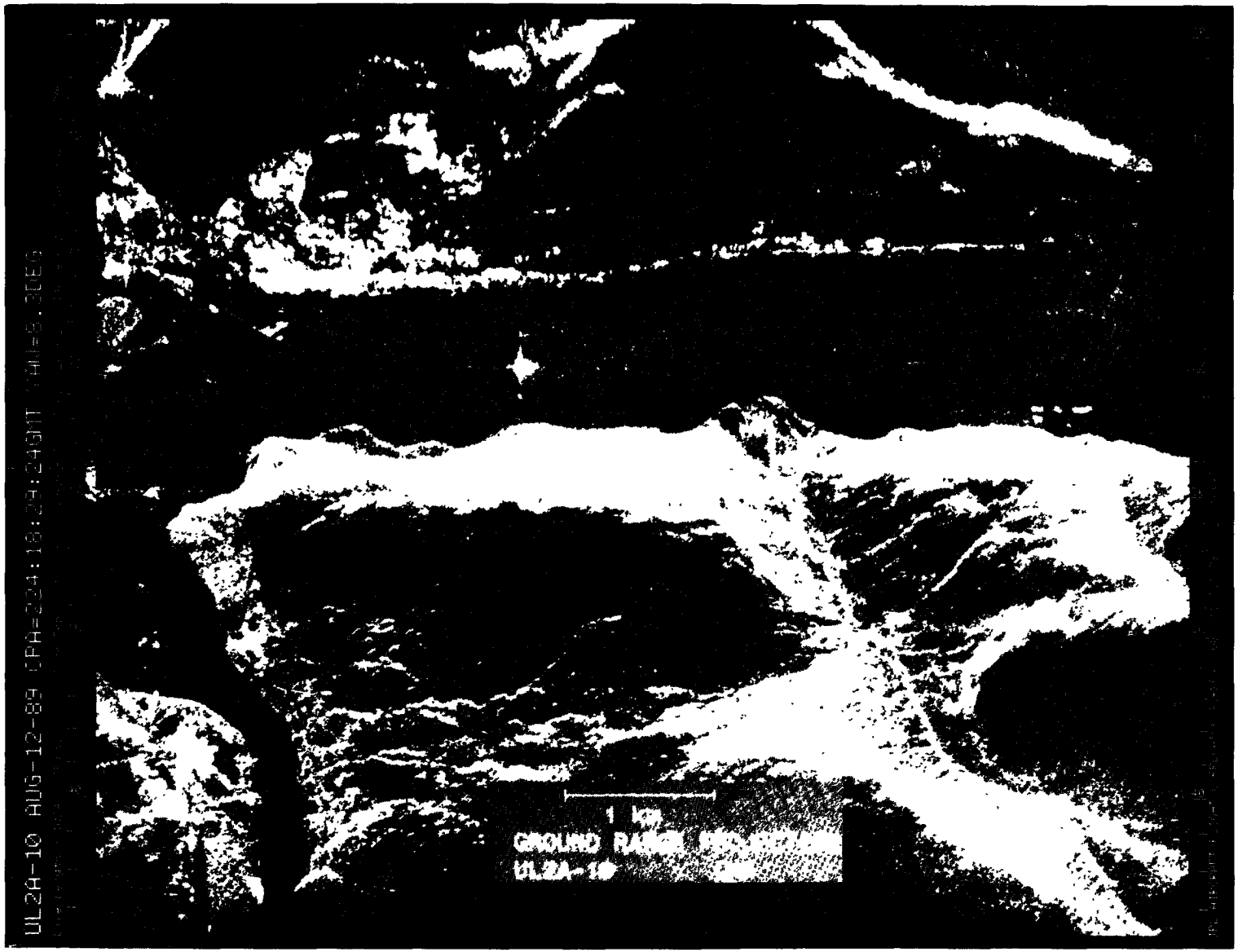

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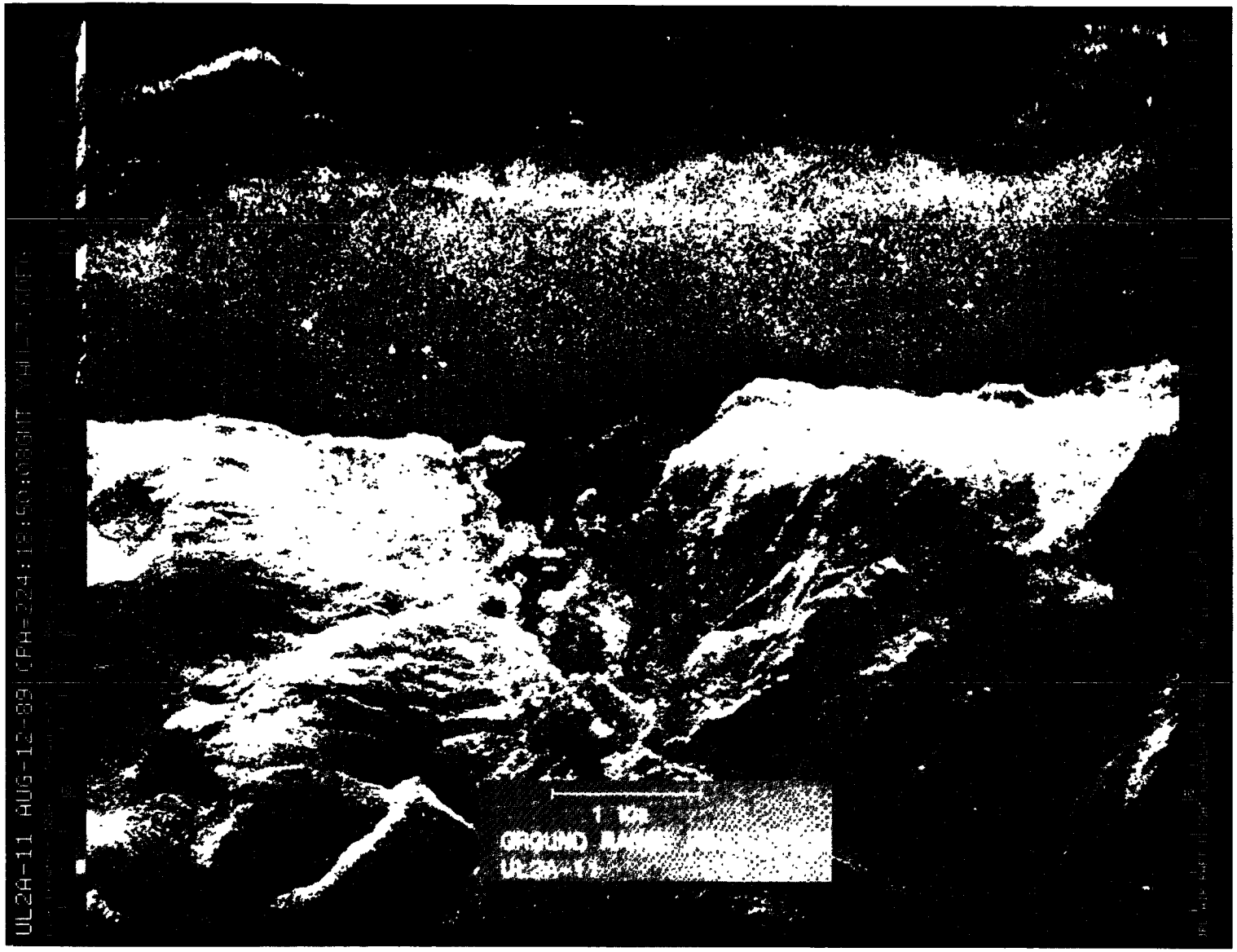

Figure A-39. August 12, 1989, Pass 11, CPA 224:18:50:08GMT LVV

Figure A-40. August 12, 1989, Pass 12, CPA 224:19:10:08GMT PVV

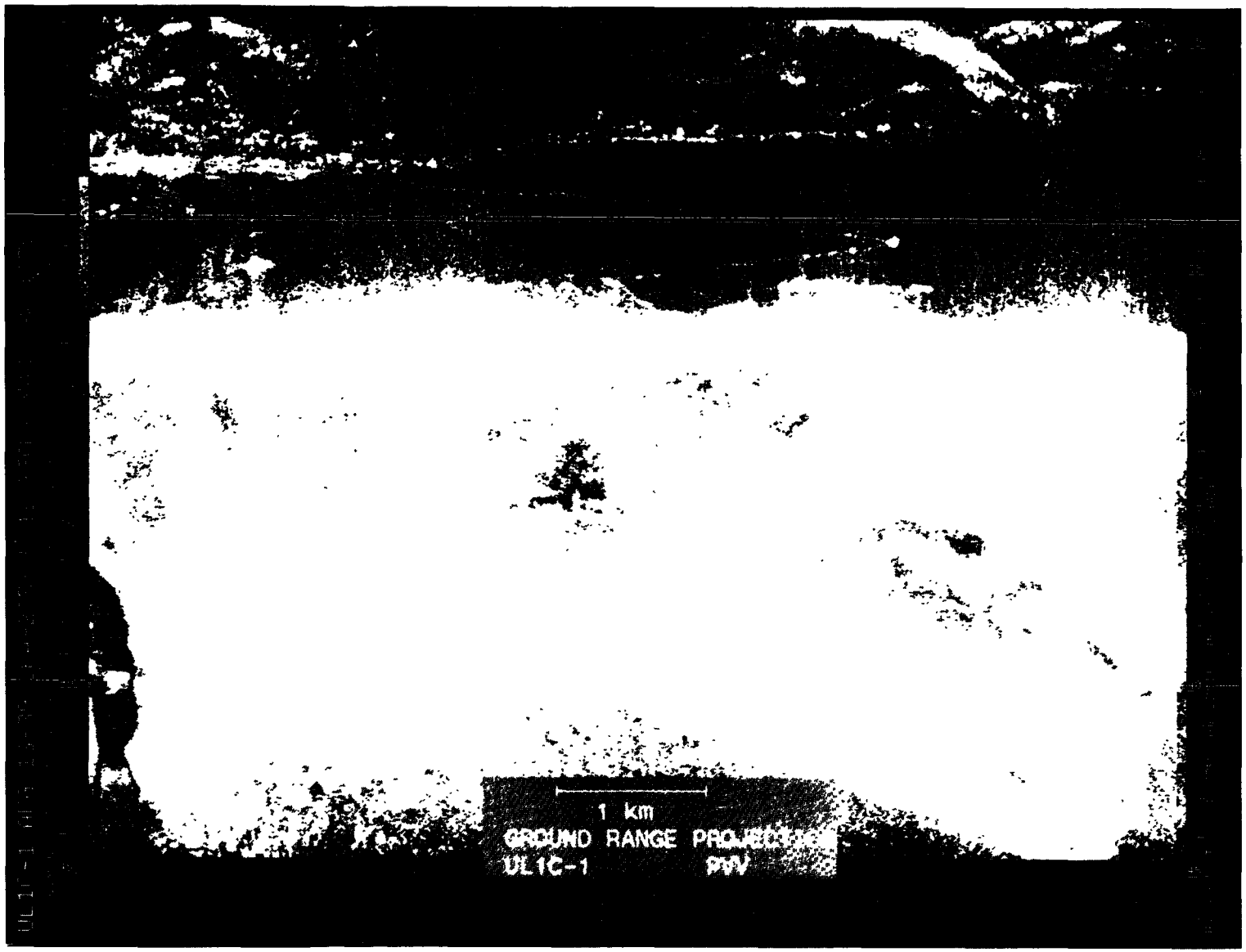

Figure A-41. August 13, 1989, Pass 1, CPA 225:15:19:35GMT PVV

Figure A-42. August 13, 1989, Pass 2, CPA 225:15:39:45GMT PVV

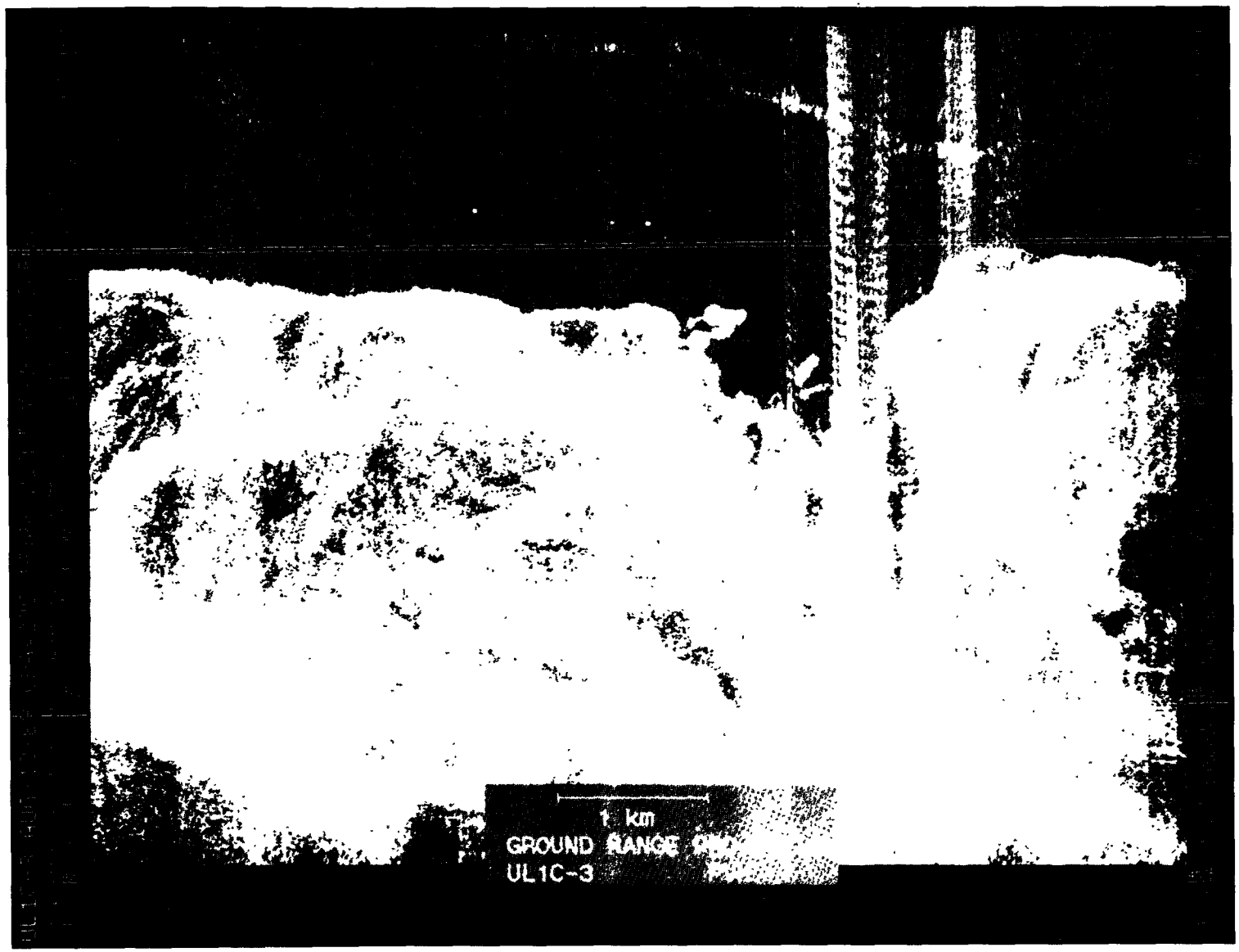

Figure A-43. August 13, 1989, Pass 3, CPA 225:16:00:23GMT PVH

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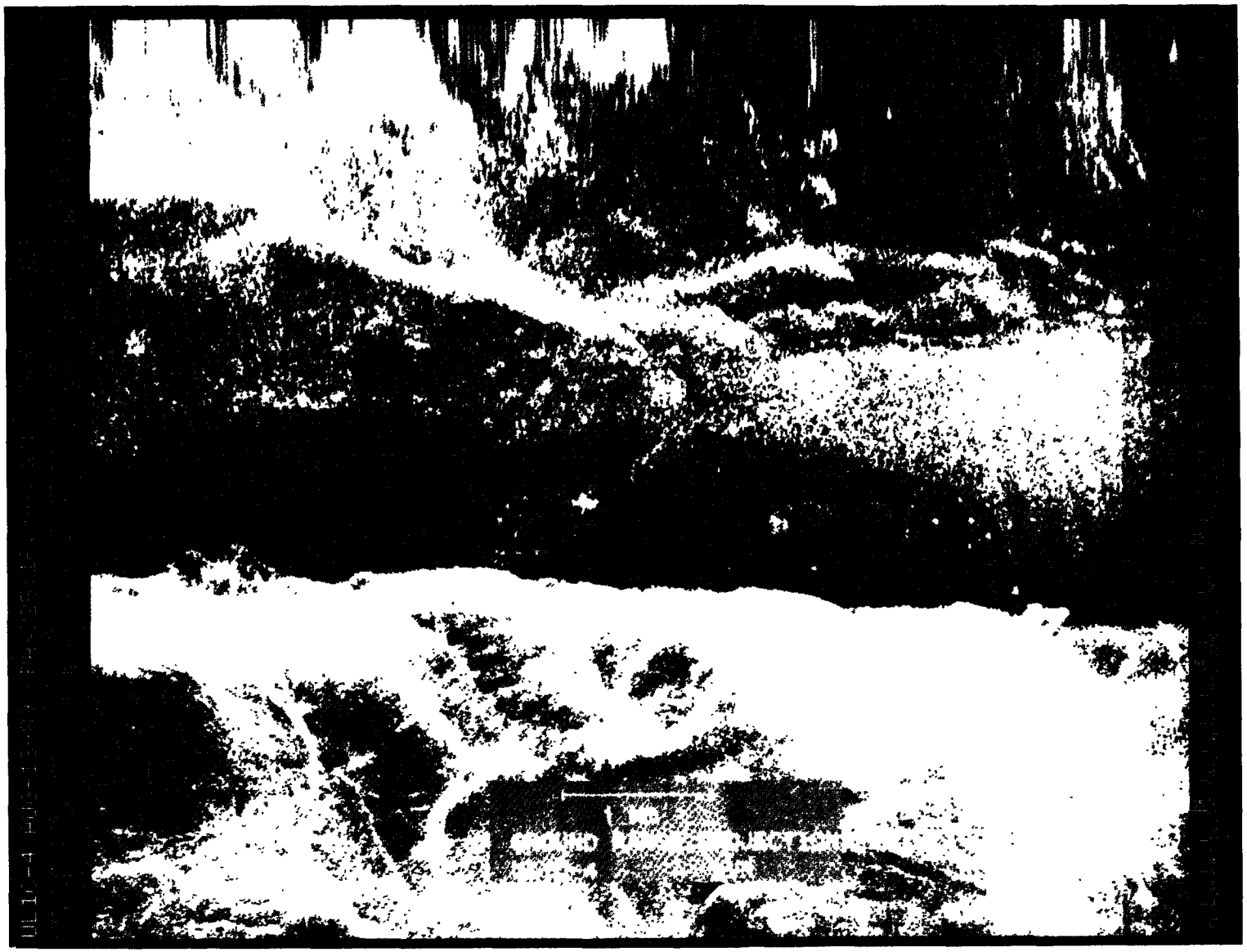

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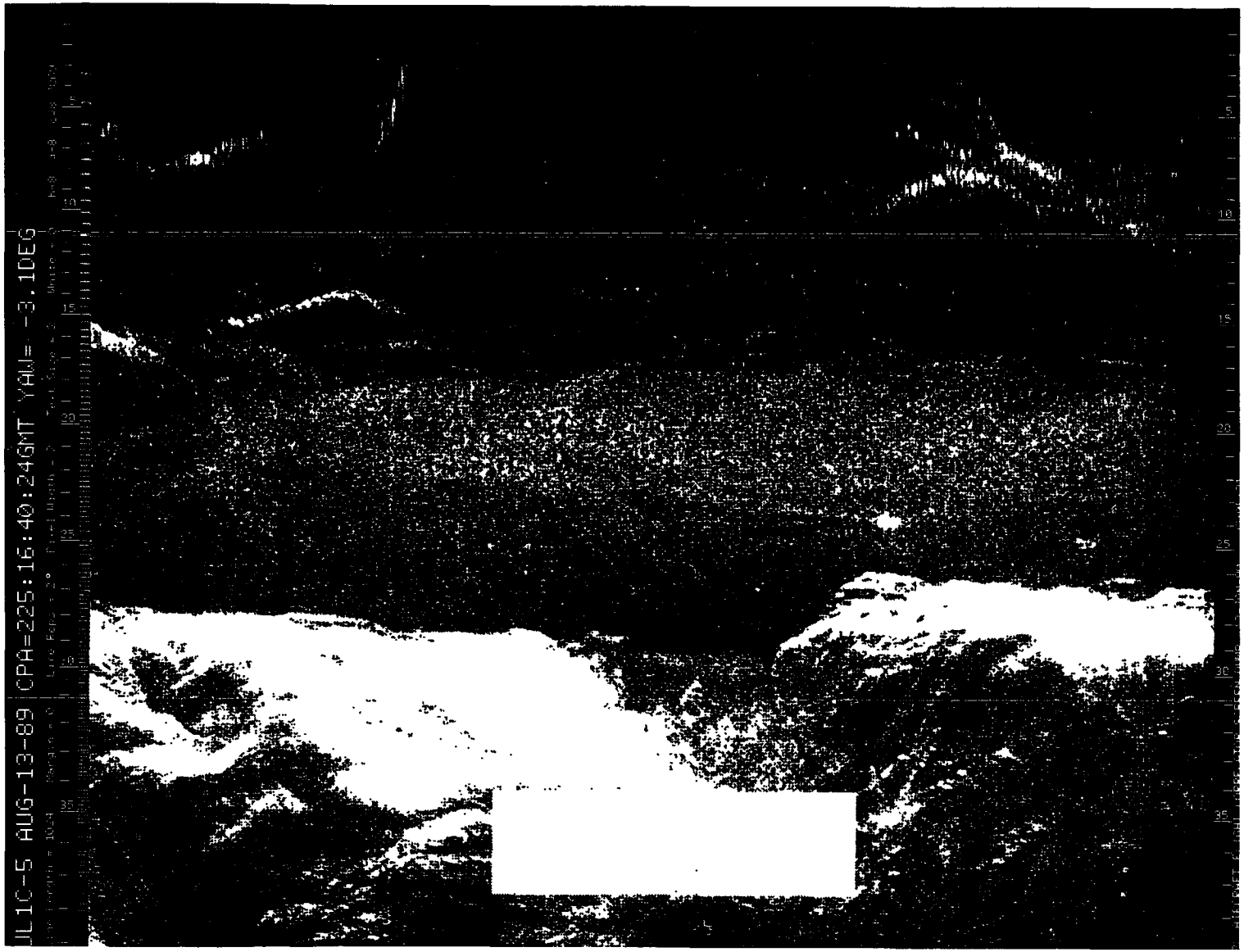

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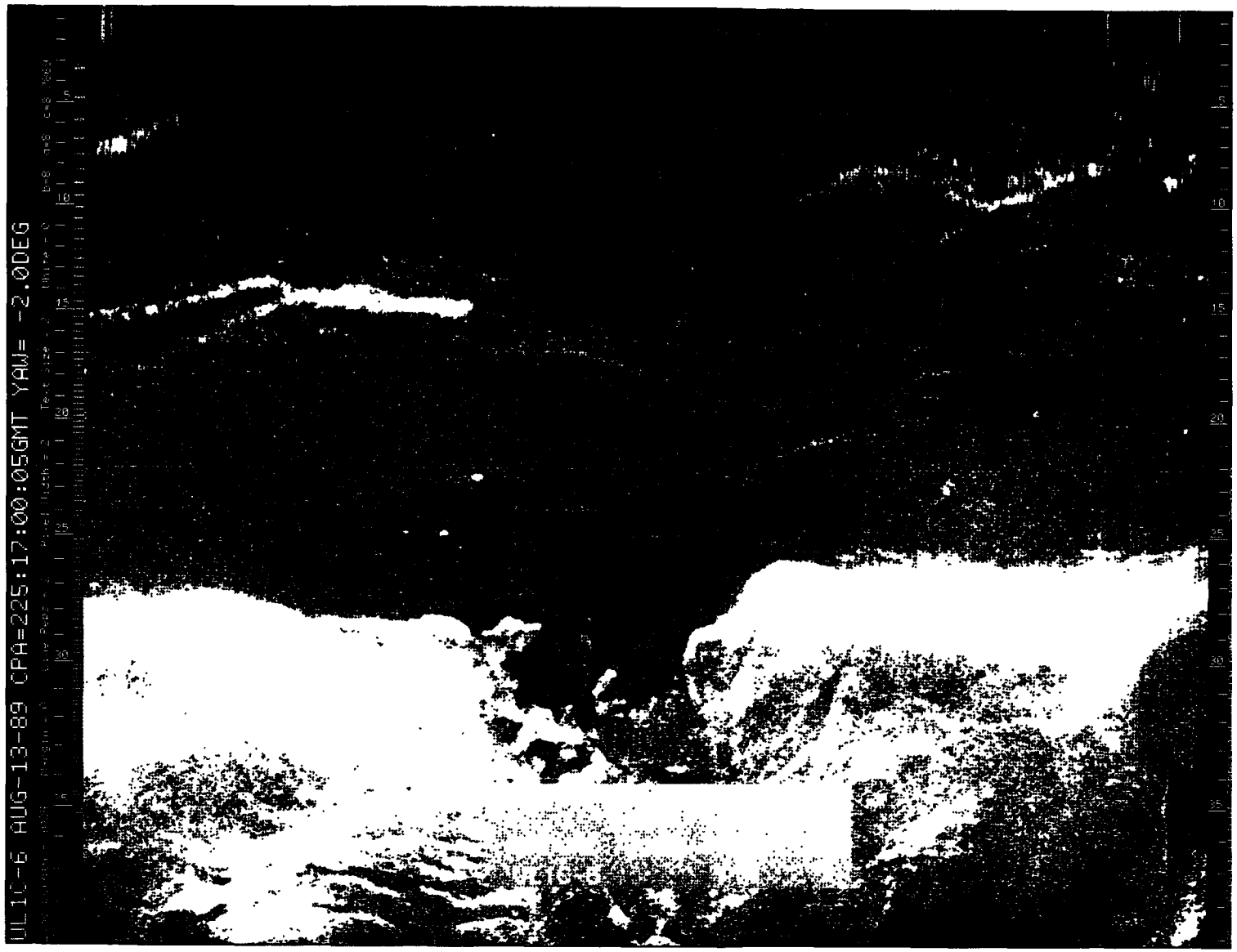

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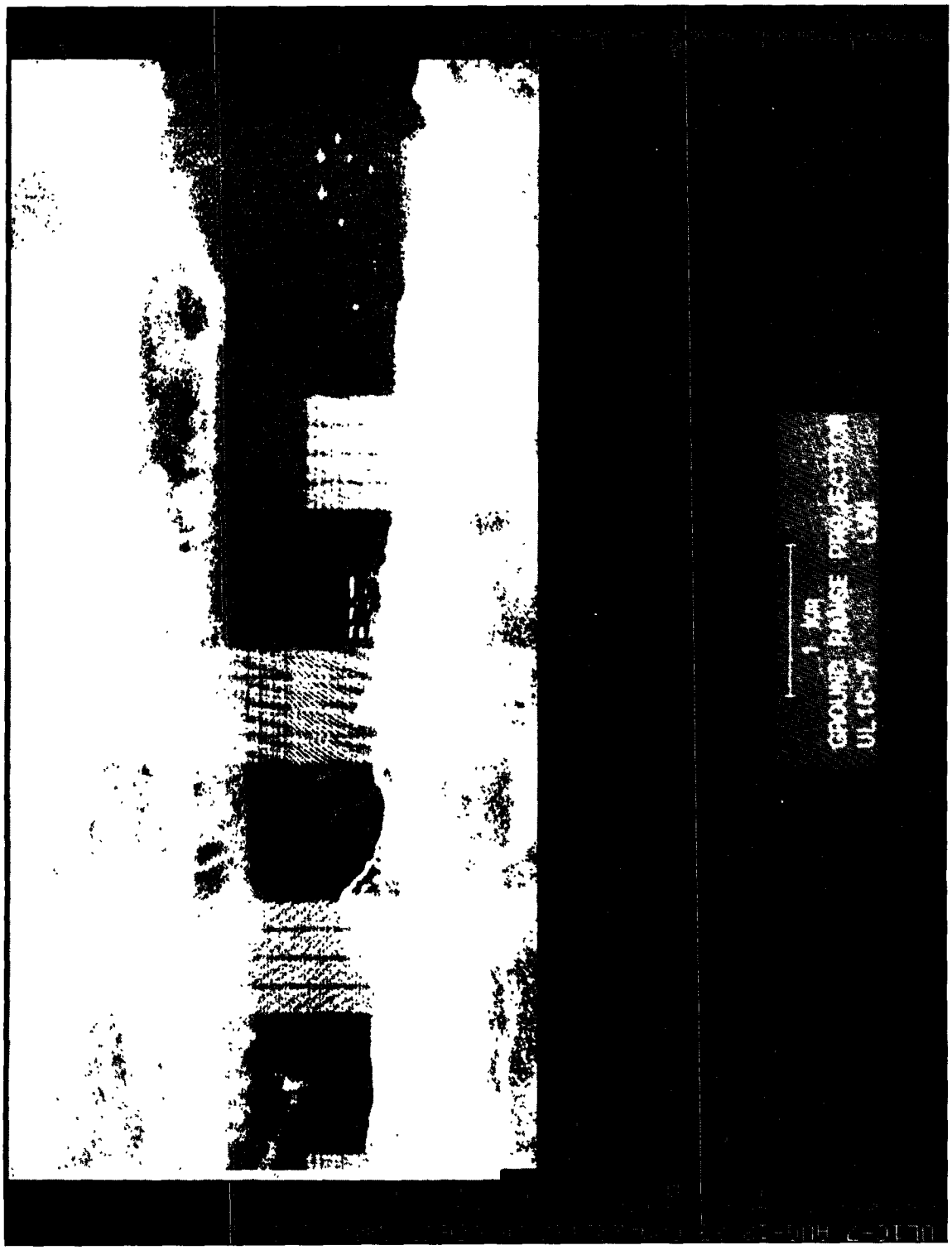

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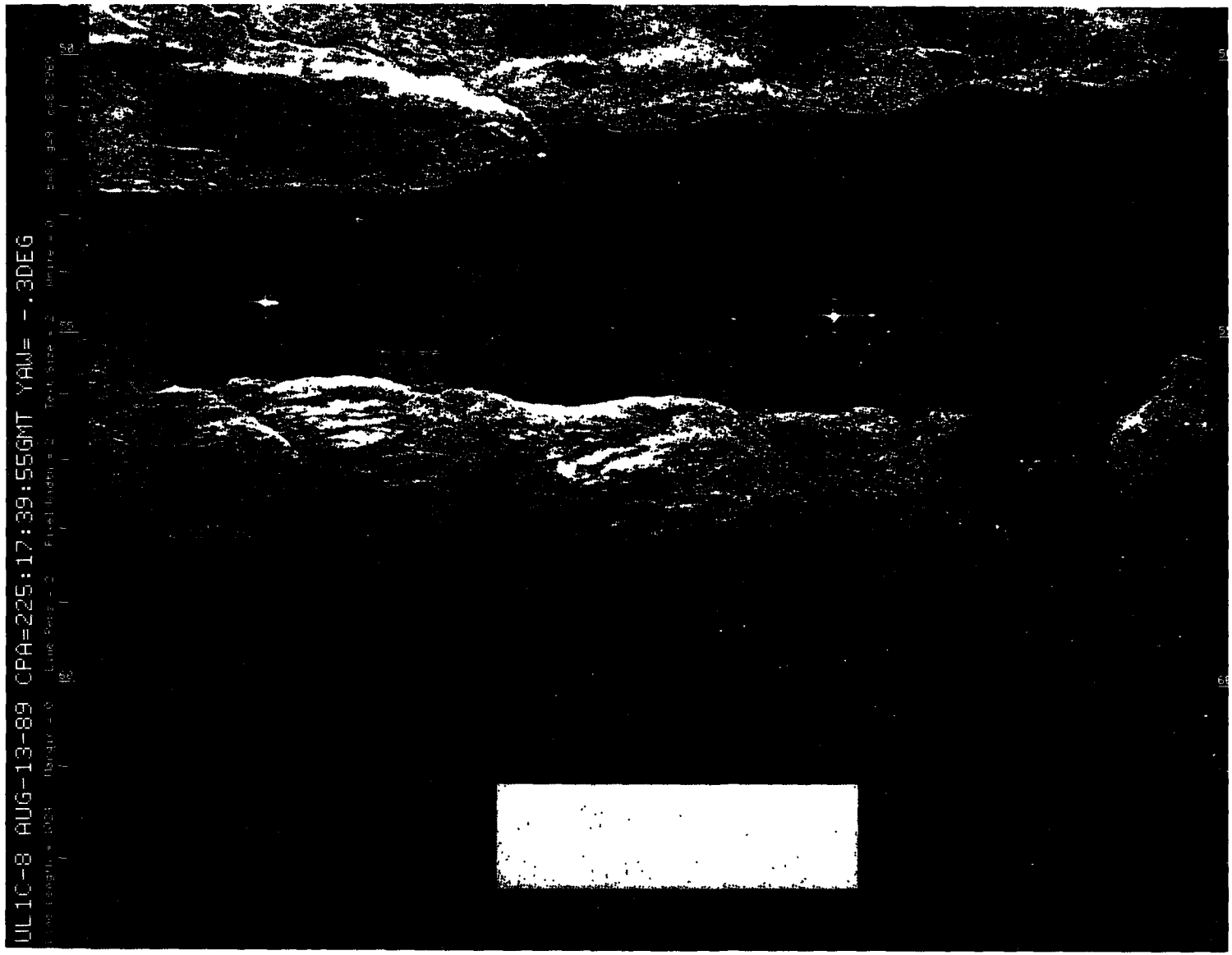

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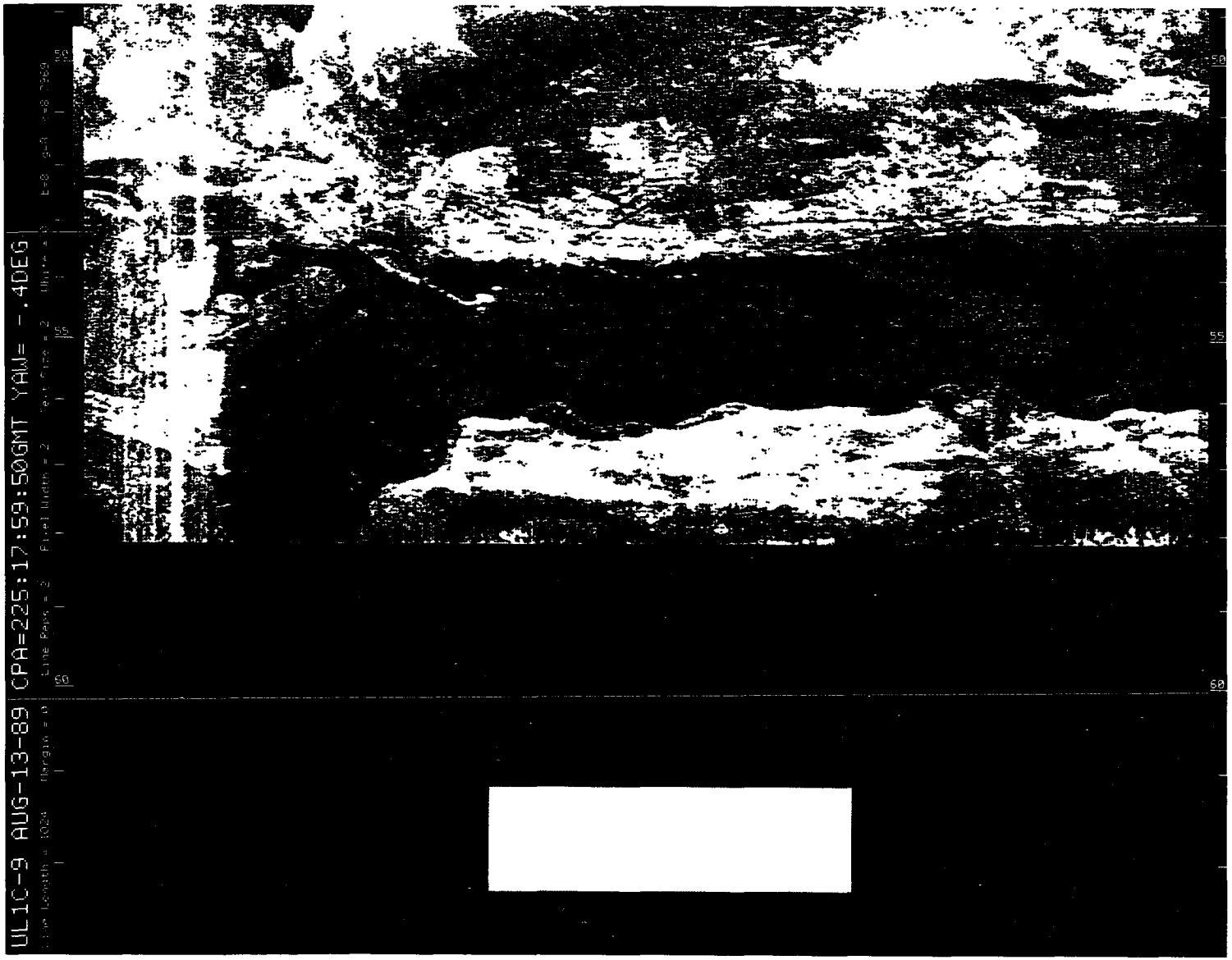

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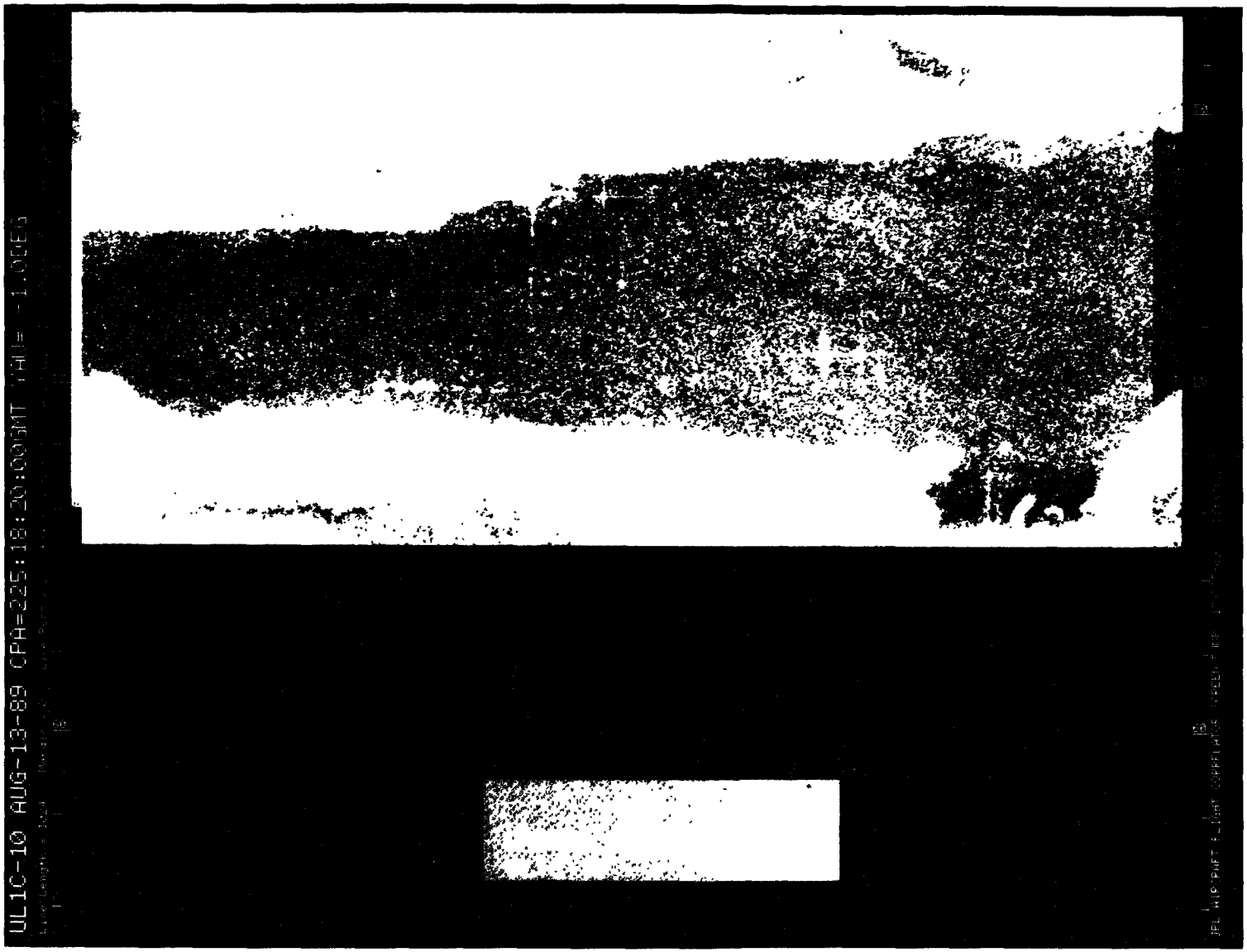

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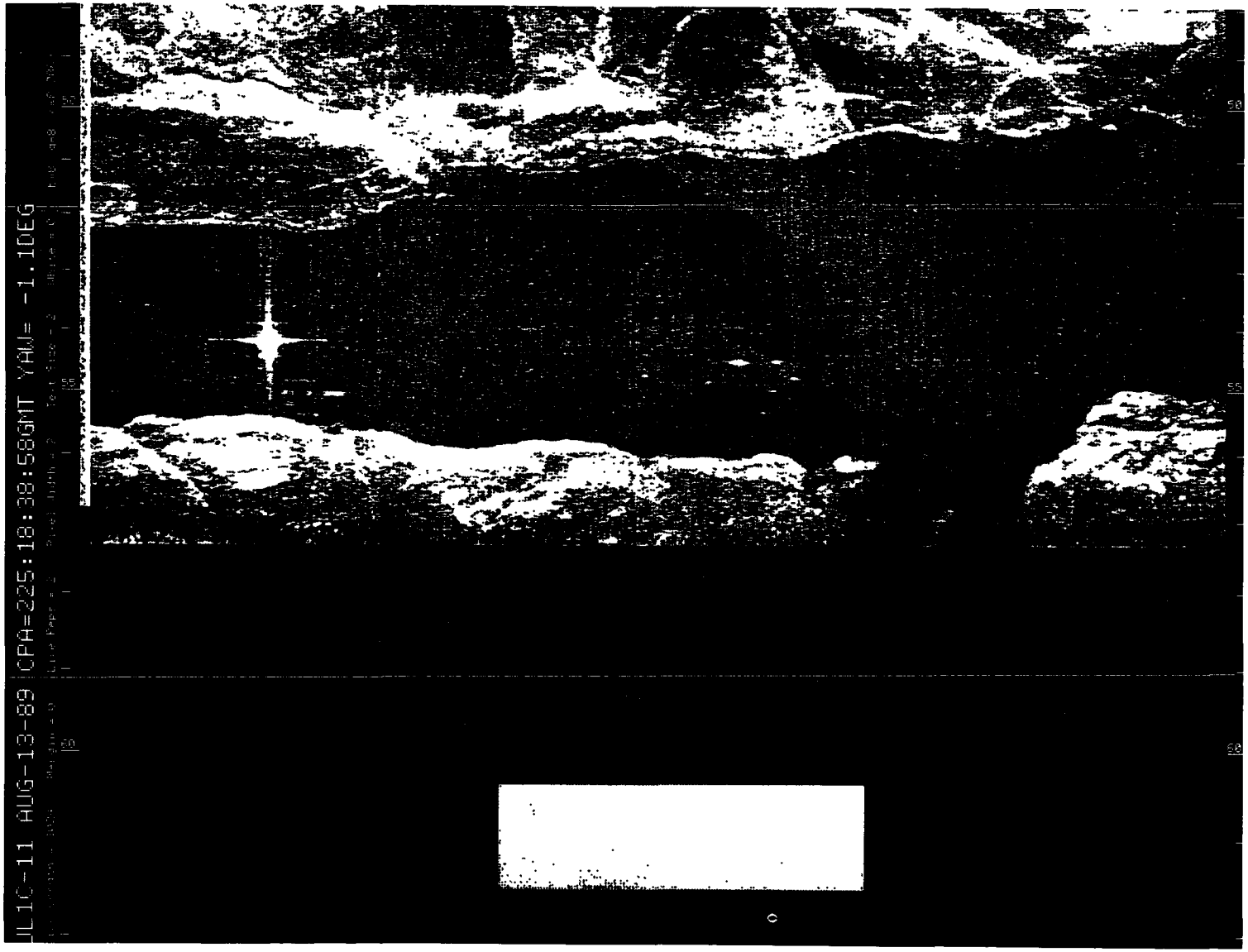

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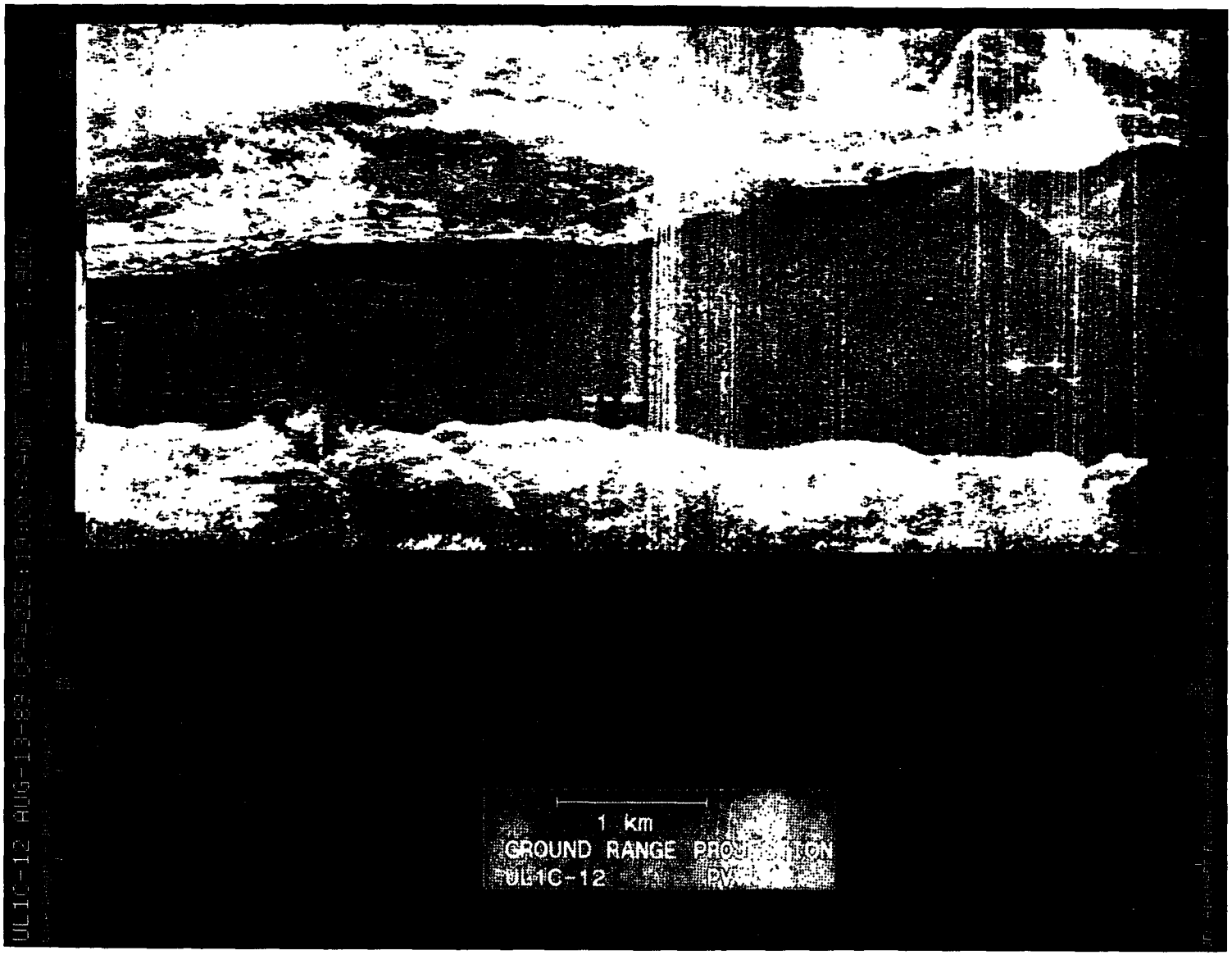


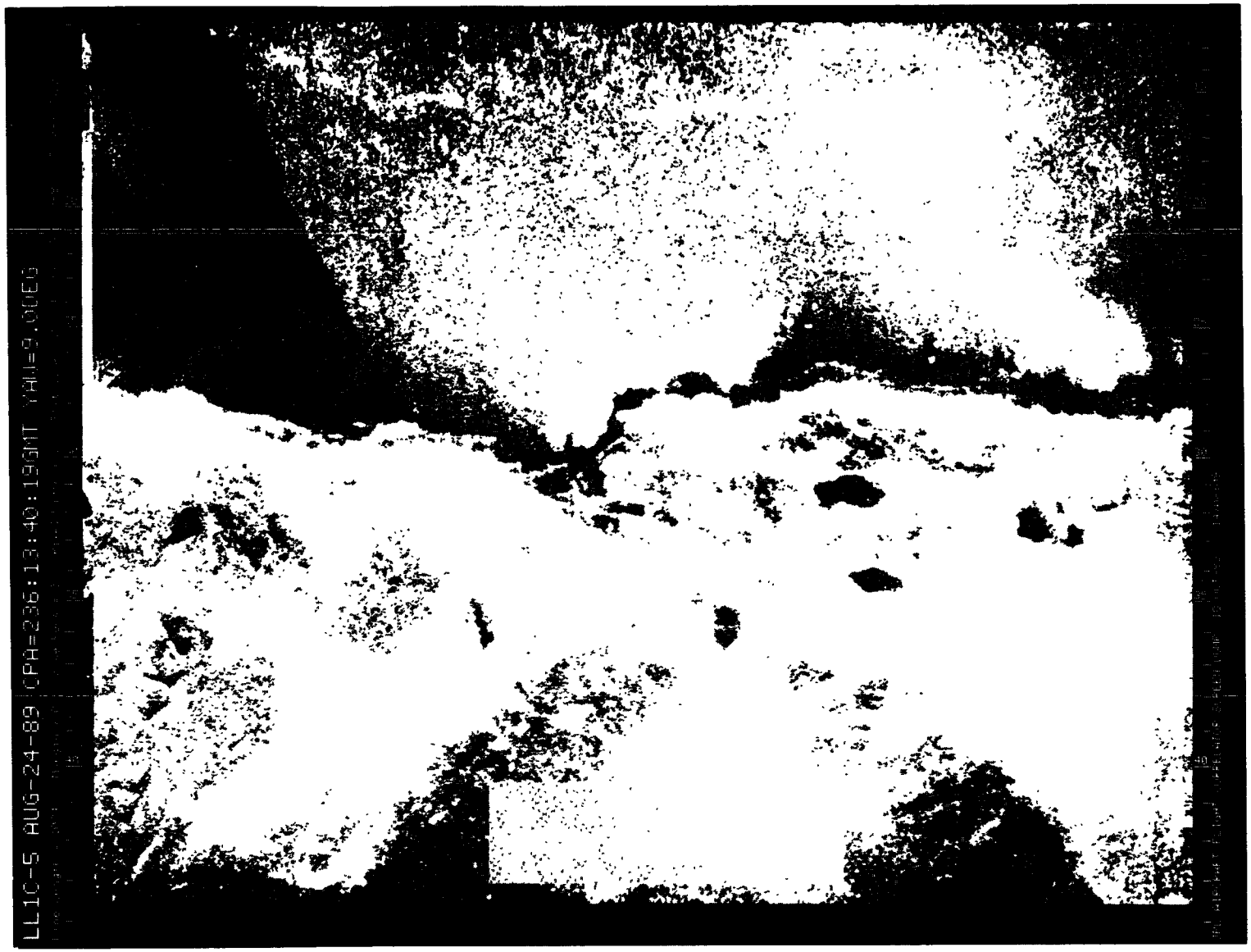
Figure A-52. August 13, 1989, Pass 12, CPA 225:19:00:04GMT PVV

Figure A-53. August 24, 1989, Pass 1, CPA 236:12:18:07GMT PVV

Figure A-54. August 24, 1989, Pass 2, CPA 236:12:40:49GMT PHH

Figure A-55. August 24, 1989, Pass 3, CPA 236:13:00:08GMT LVV

Figure A-56. August 24, 1989, Pass 4, CPA 236:13:20:37GMT LHH



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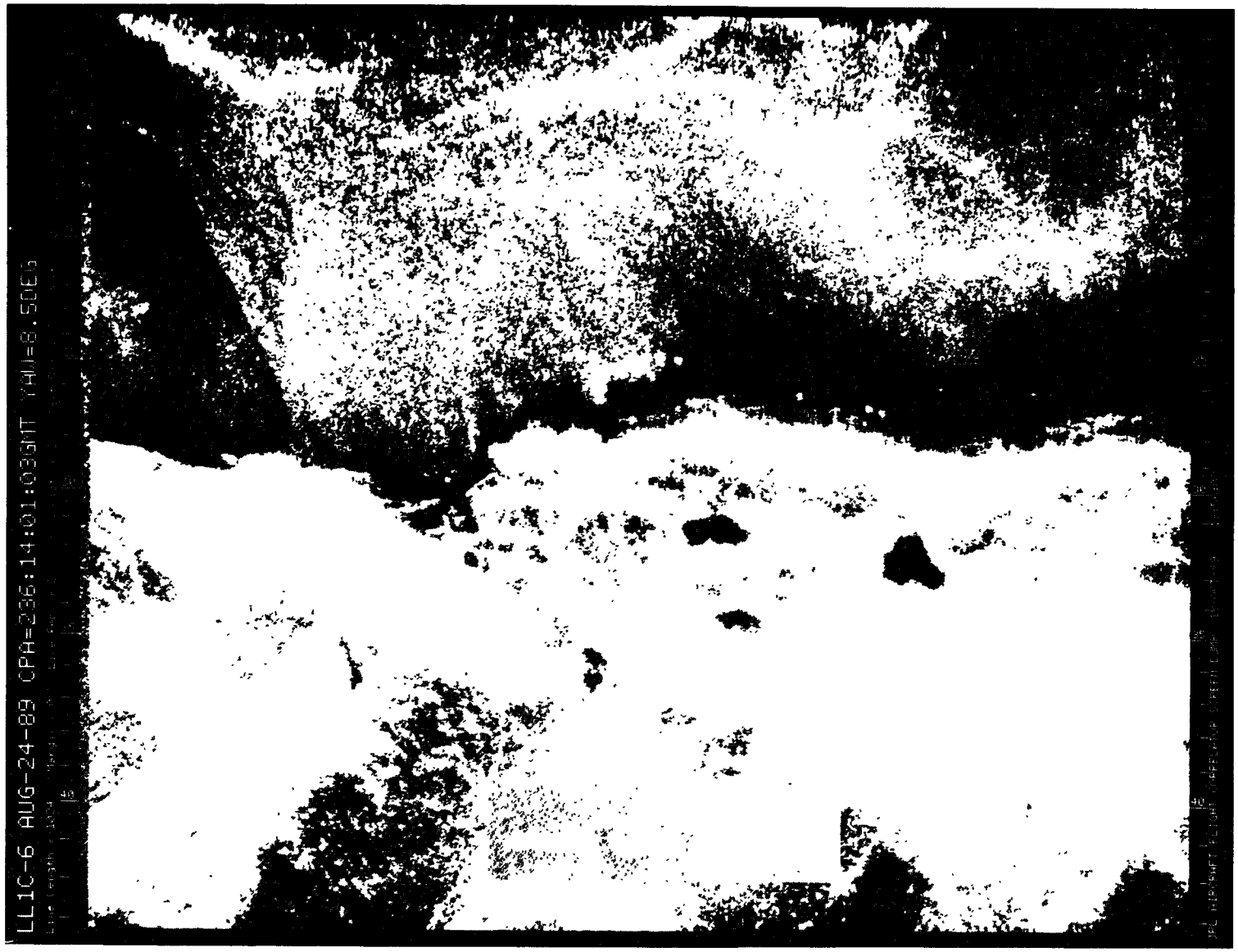

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Figure A-59. August 24, 1989, Pass 7, CPA 236:14:20:41GMT PVV

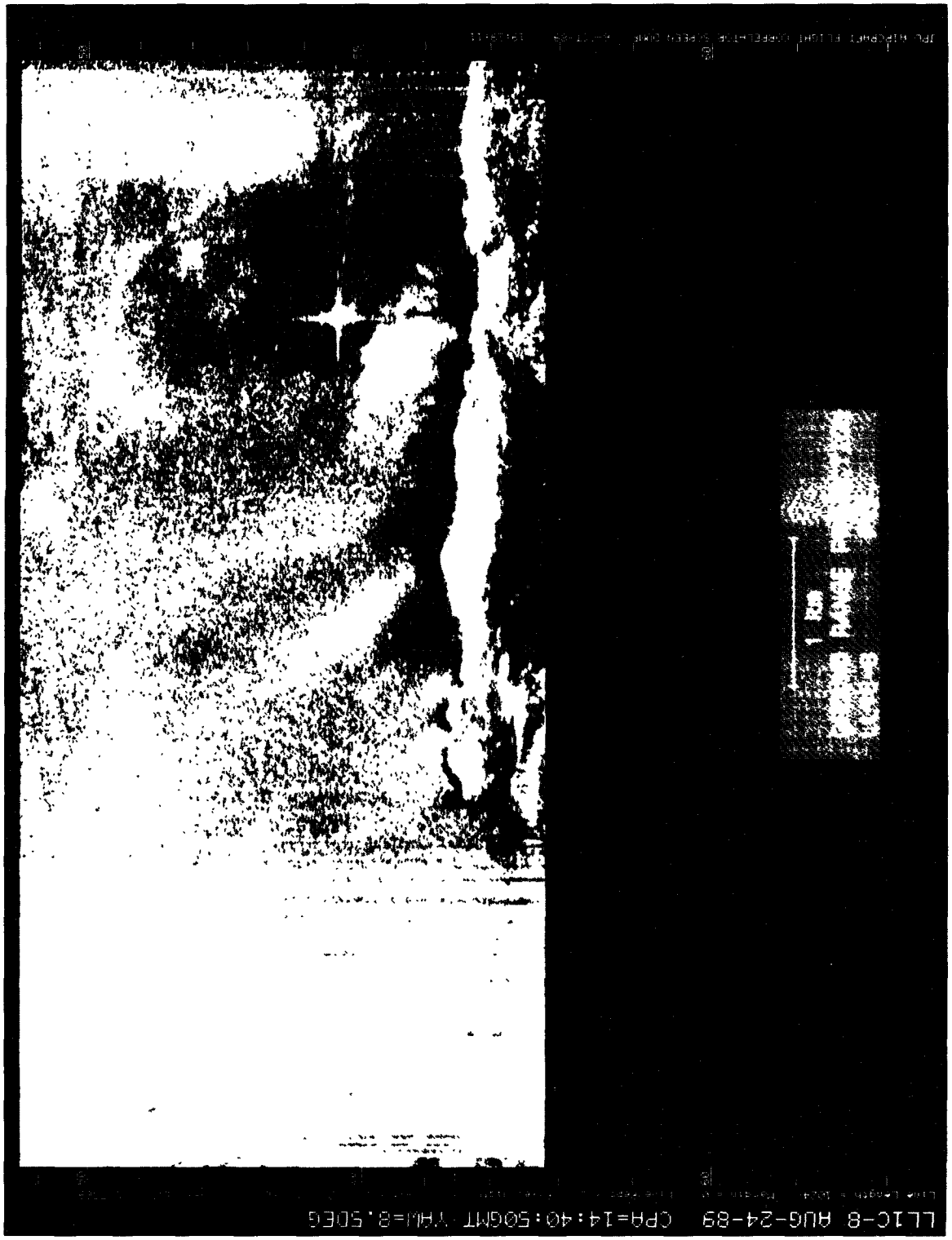

Figure A-60. August 24, 1989, Pass 8, CPA 236:14:40:50GMT PVV

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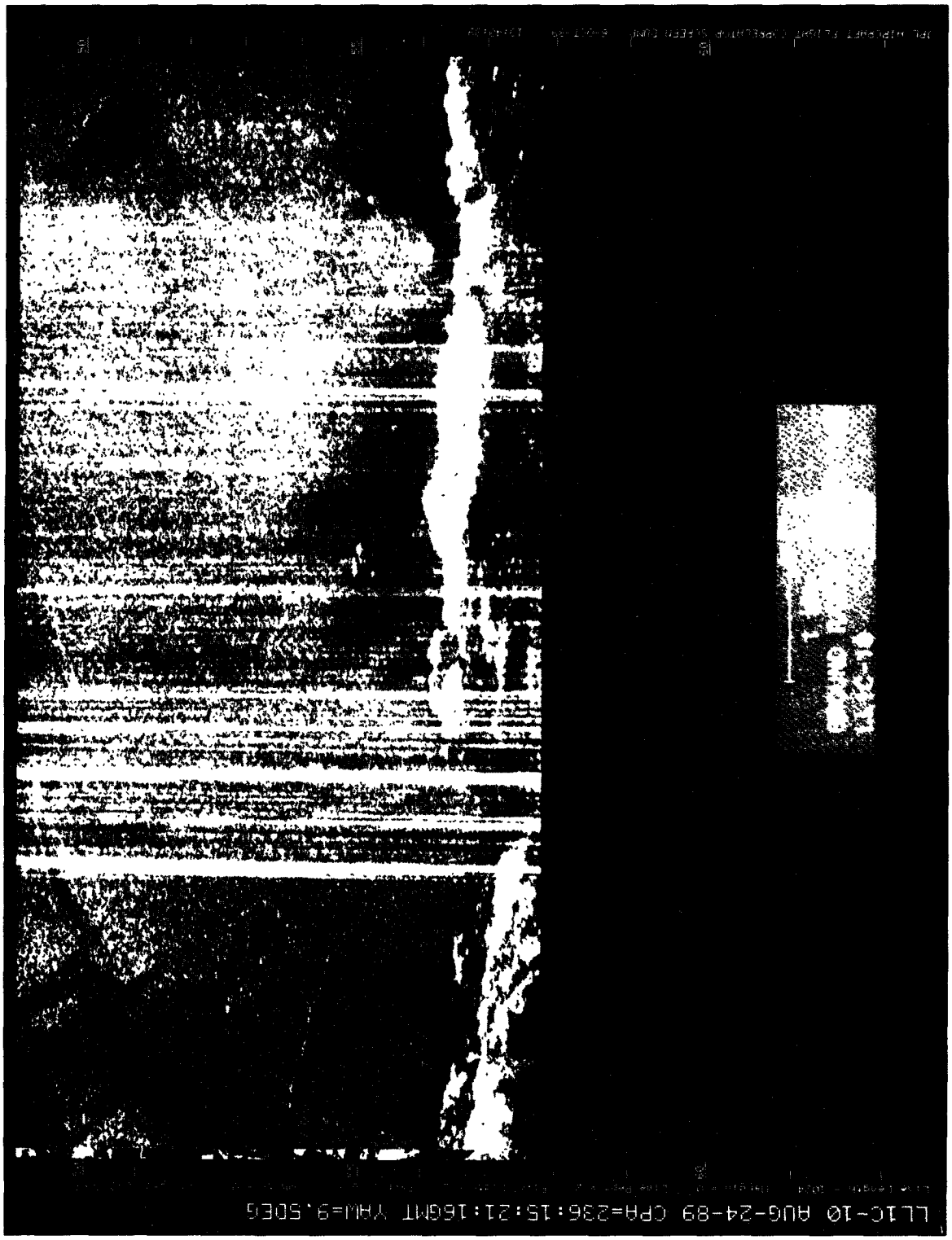
Figure A-61. August 24, 1989, Pass 9, CPA 236:15:01:33GMT PVV



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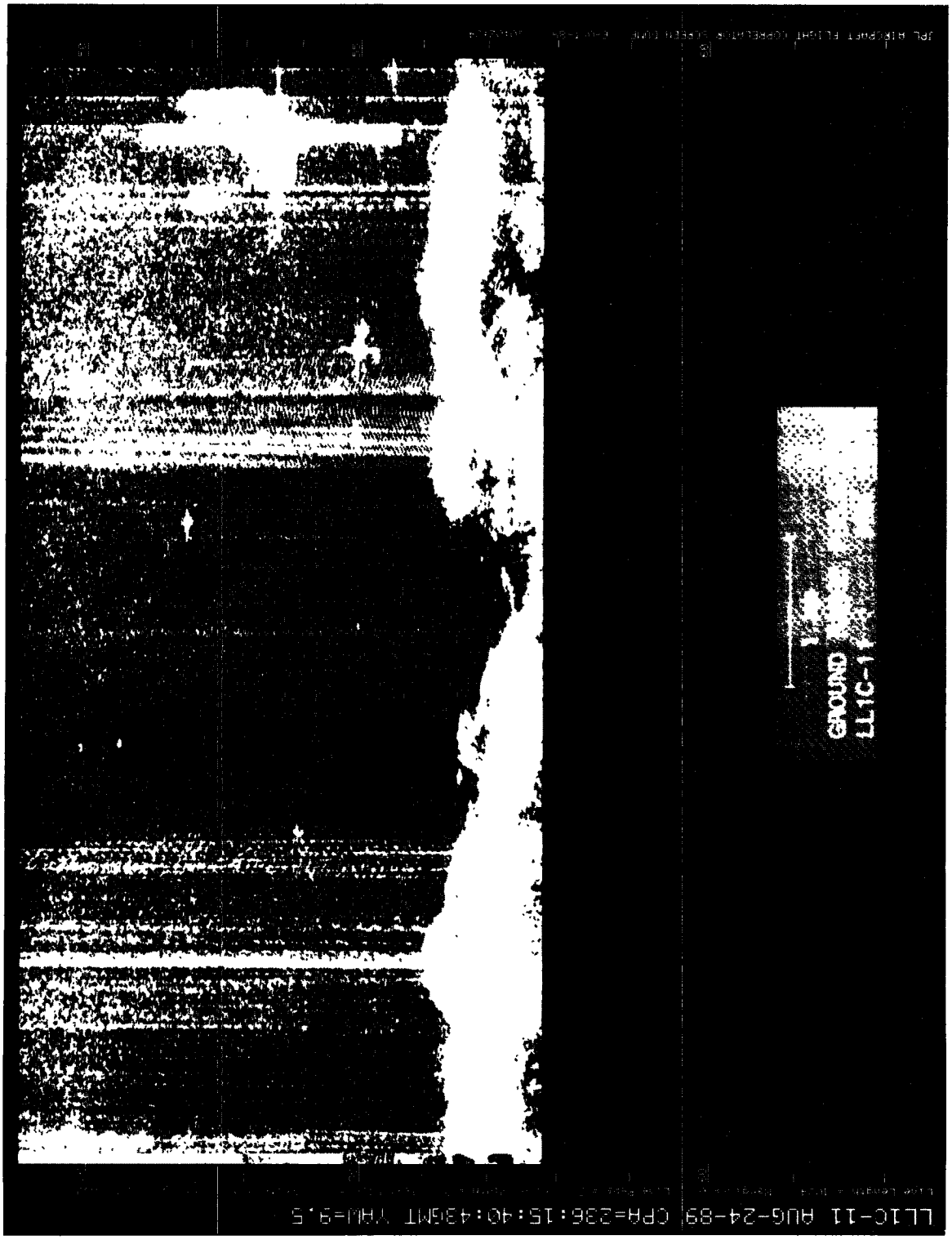

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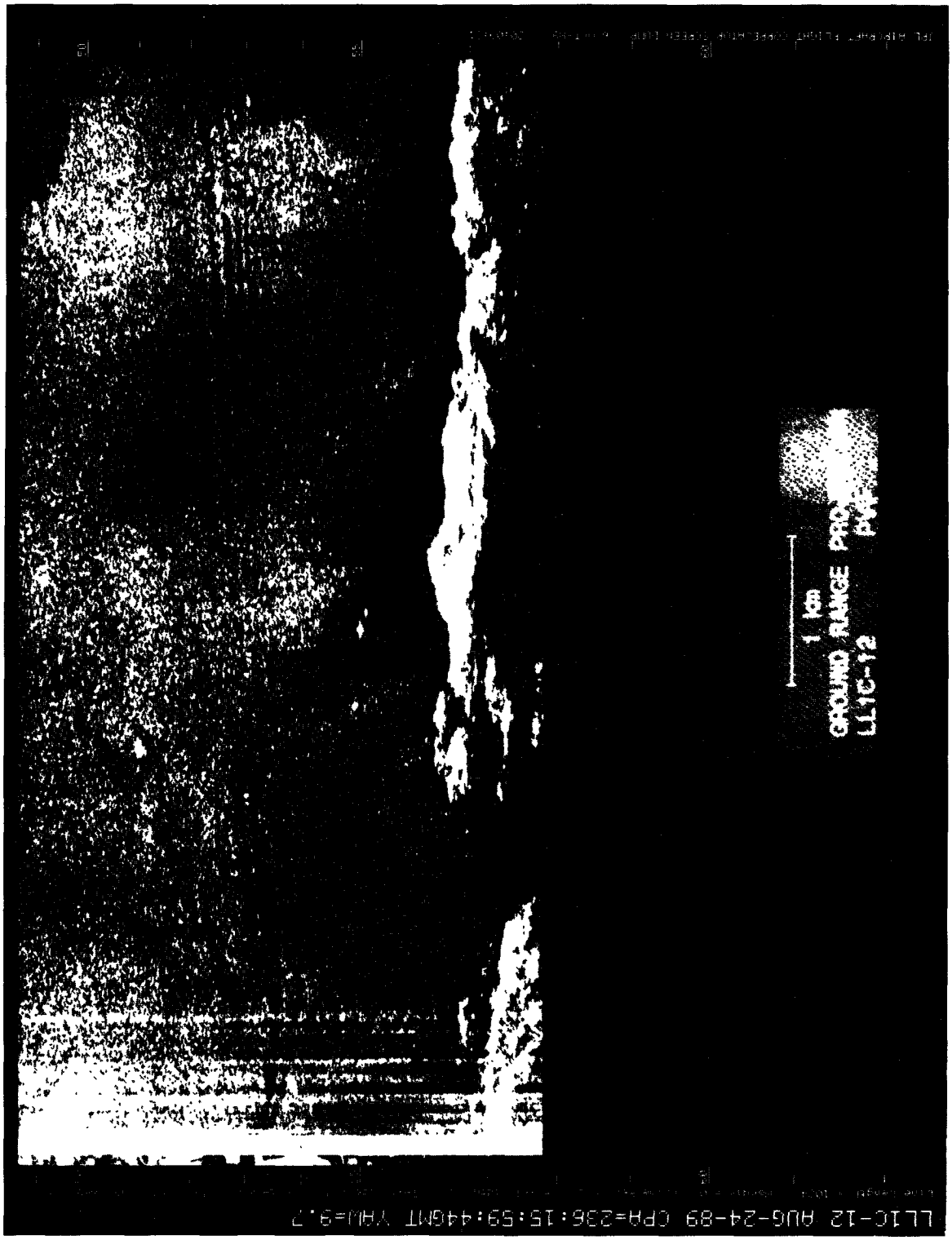

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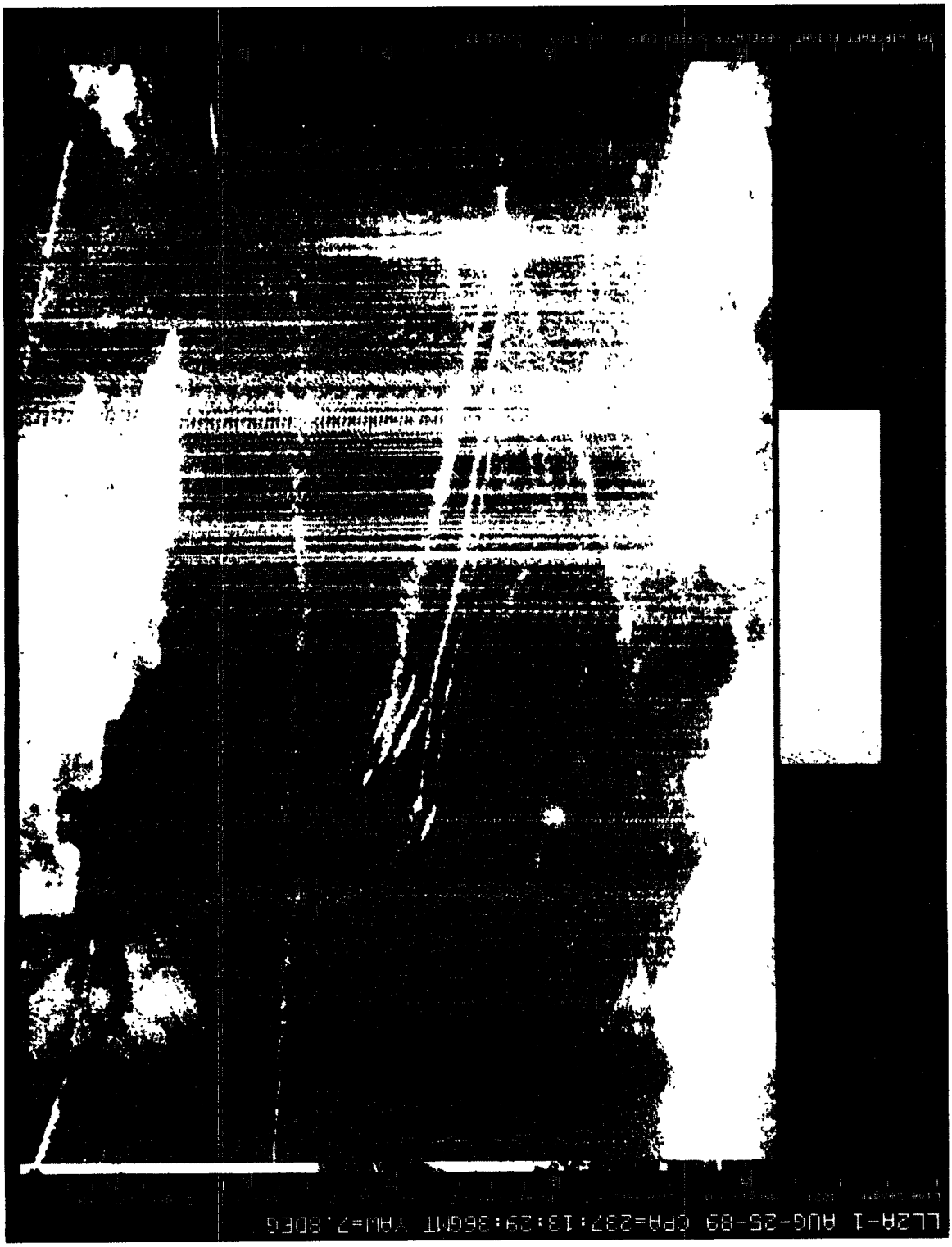

Figure A-65. August 25, 1989, Pass 1, CPA 237:13:29:36GMT PVV

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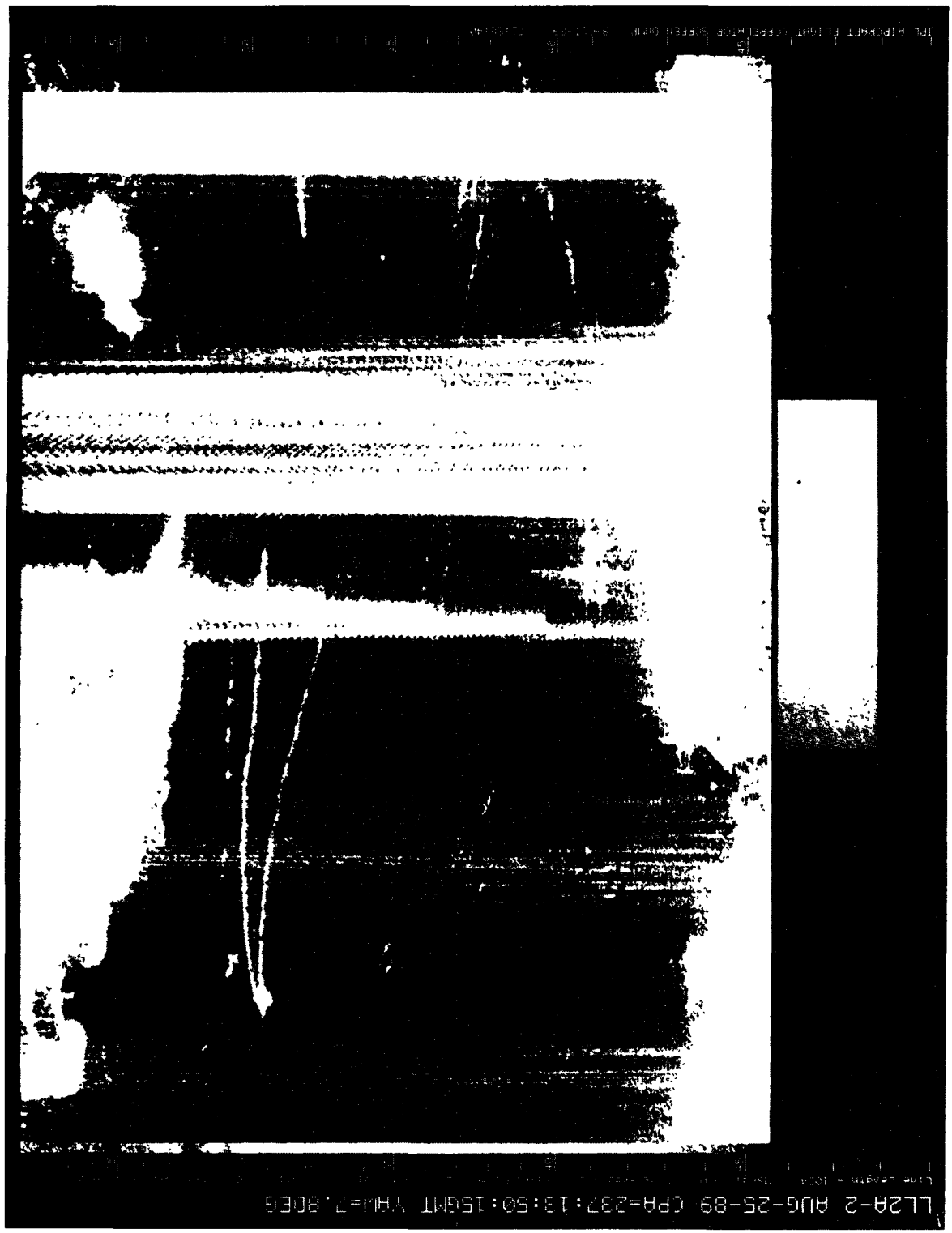

Figure A-66. August 25, 1989, Pass 2, CPA 237:13:50:15GMT PHH

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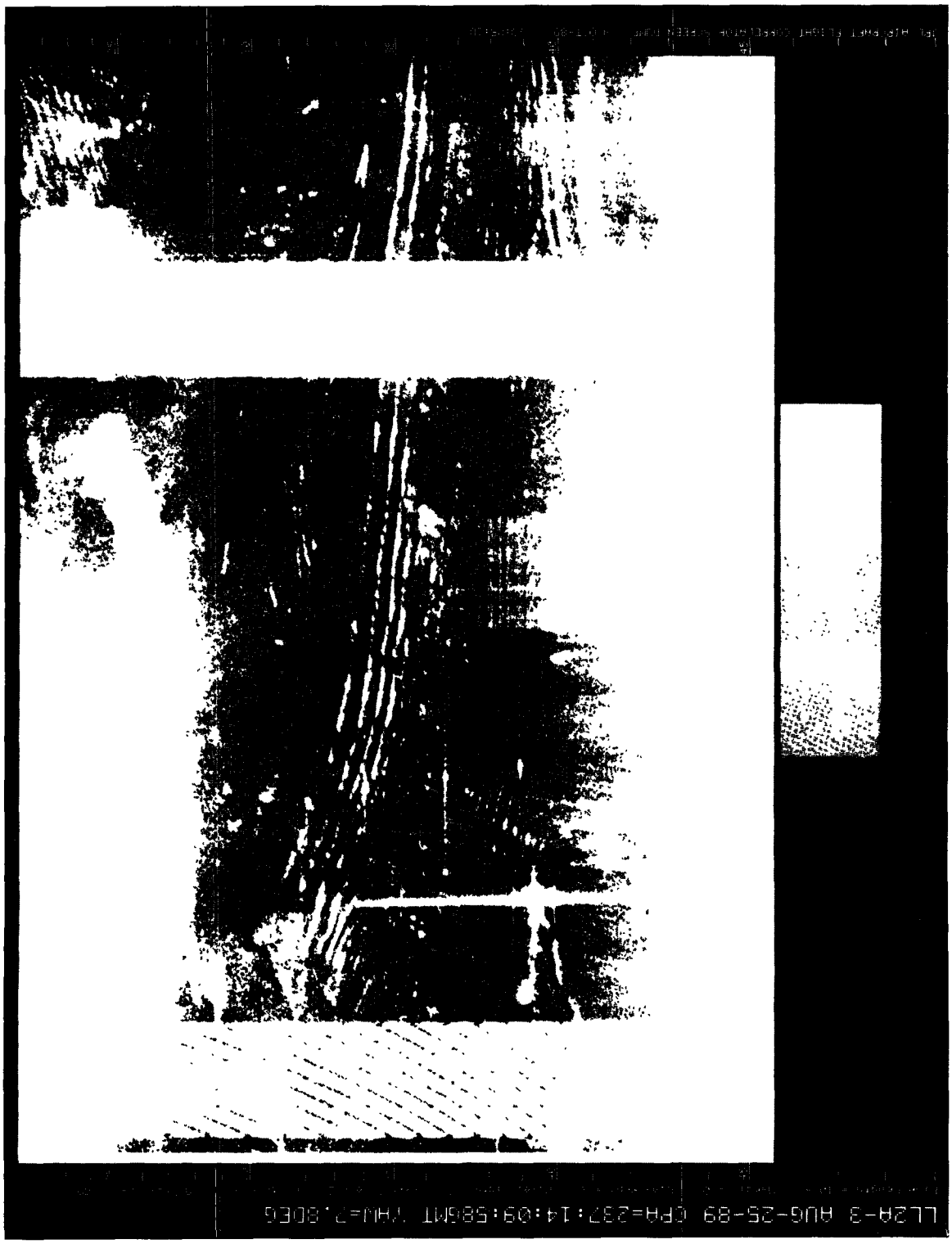

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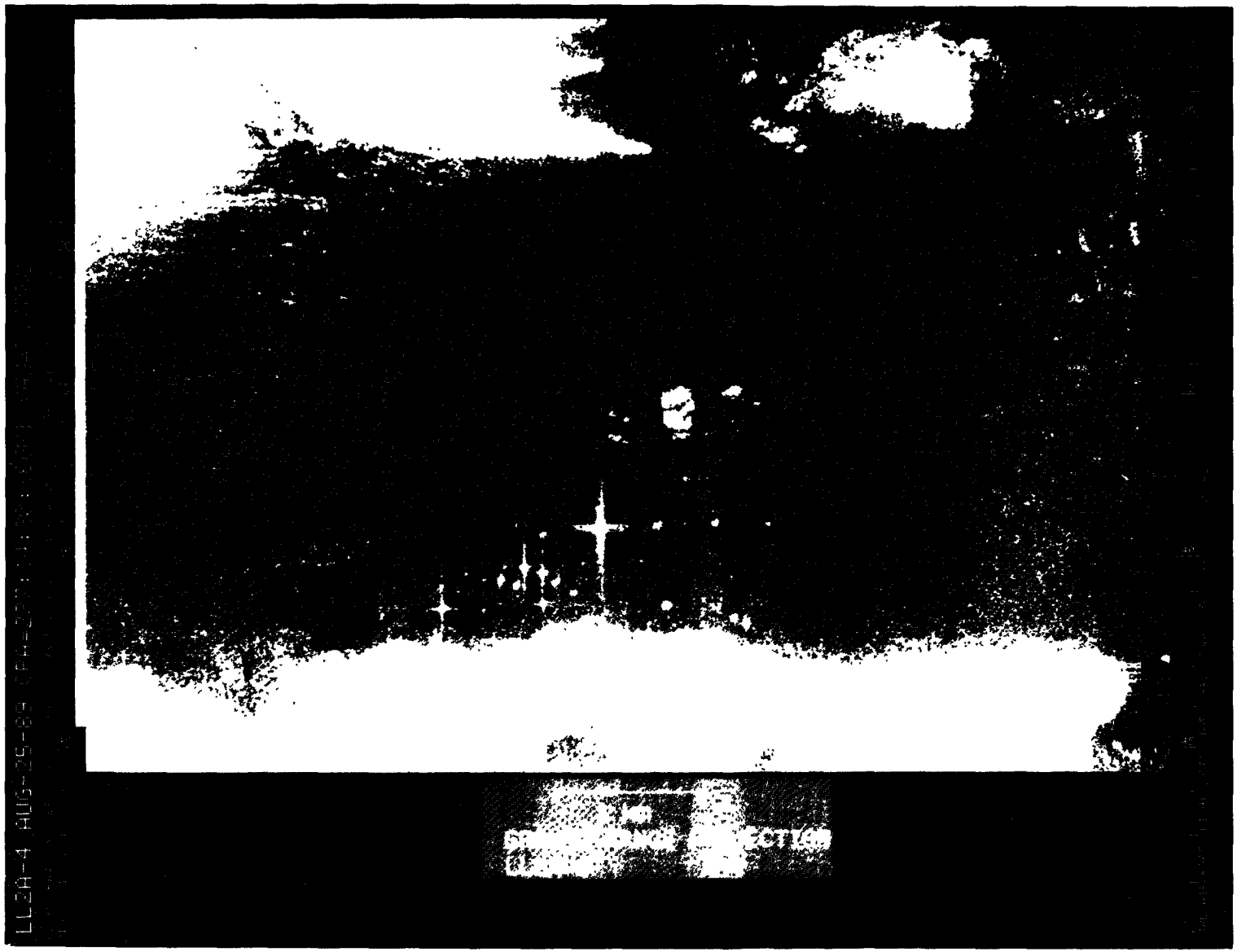

Figure A-68. August 25, 1989, Pass 4, CPA 237:14:30:36GMT CVV

Figure A-69. August 25, 1989, Pass 4, CPA 237:14:30:36GMT PVV

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Figure A-70. August 25, 1989, Pass 4, CPA 237:14:30:36GMT LHH

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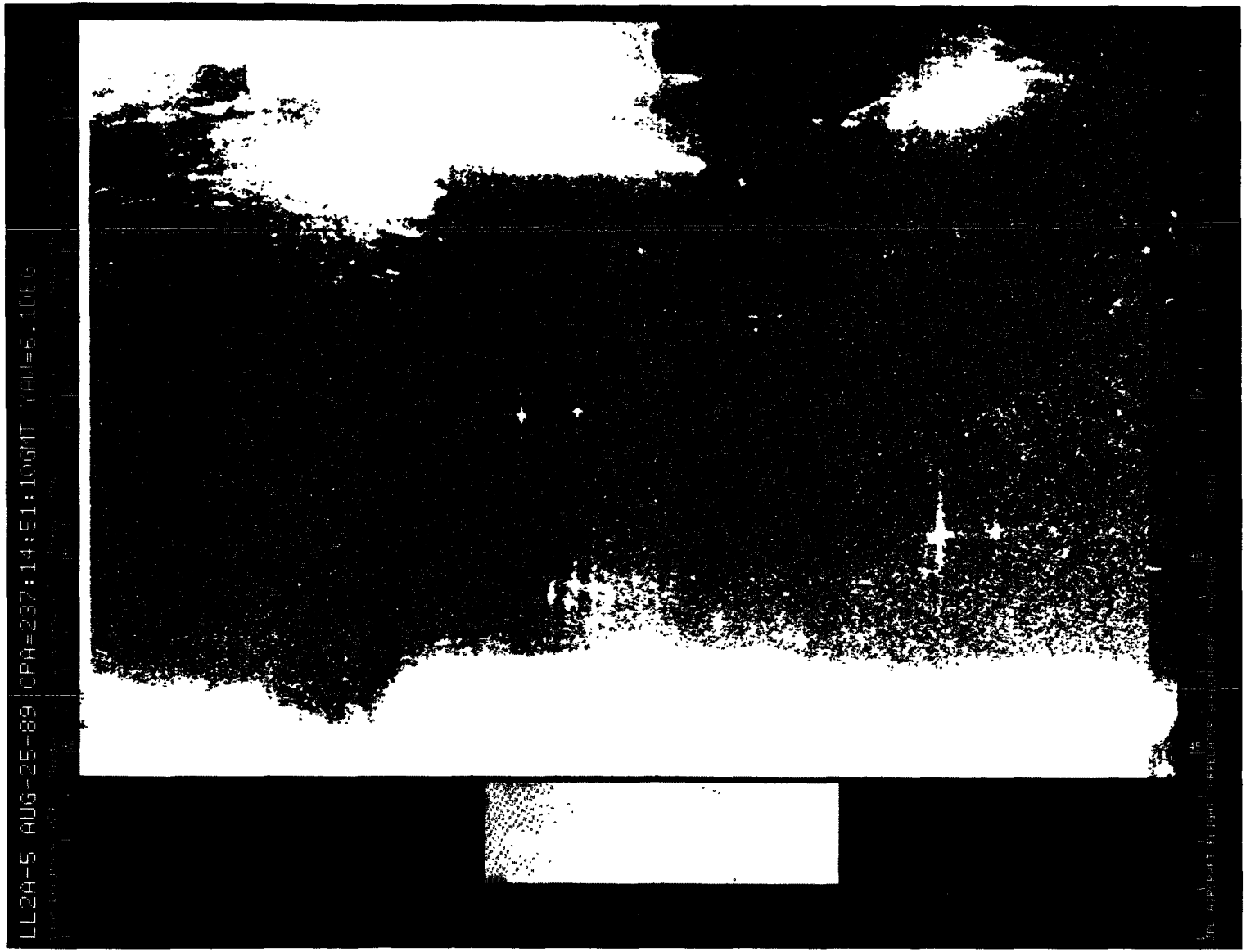

Figure A-71. August 25, 1989, Pass 5, CPA 237:14:51:10GMT CVV

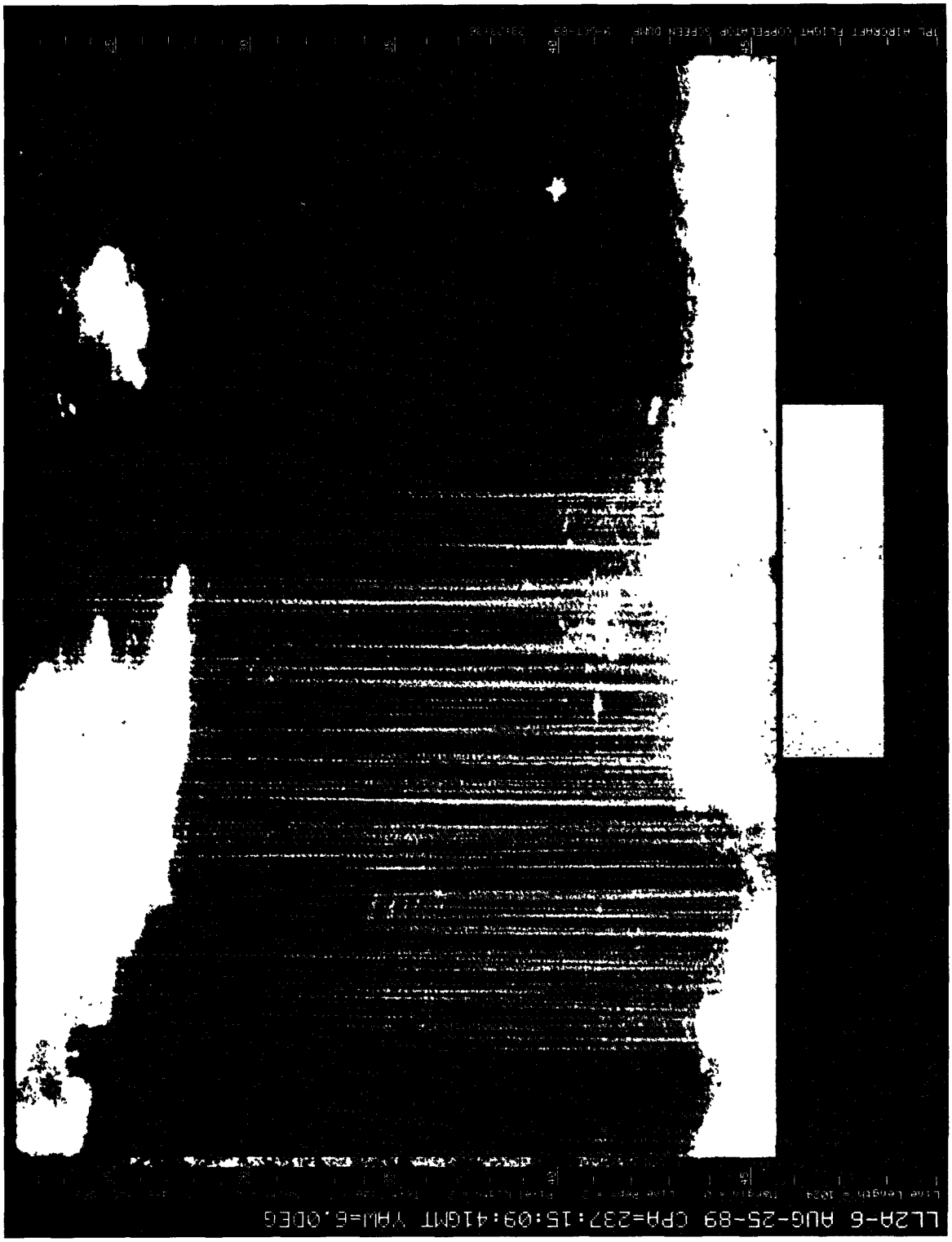

Figure A-72. August 25, 1989, Pass 6, CPA 237:15:09:41GMT PVV

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Figure A-73. August 25, 1989, Pass 7, CPA 237:15:30:30GMT LVV

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Figure A-74. August 25, 1989, Pass 8, CPA 237:15:49:48GMT LVV

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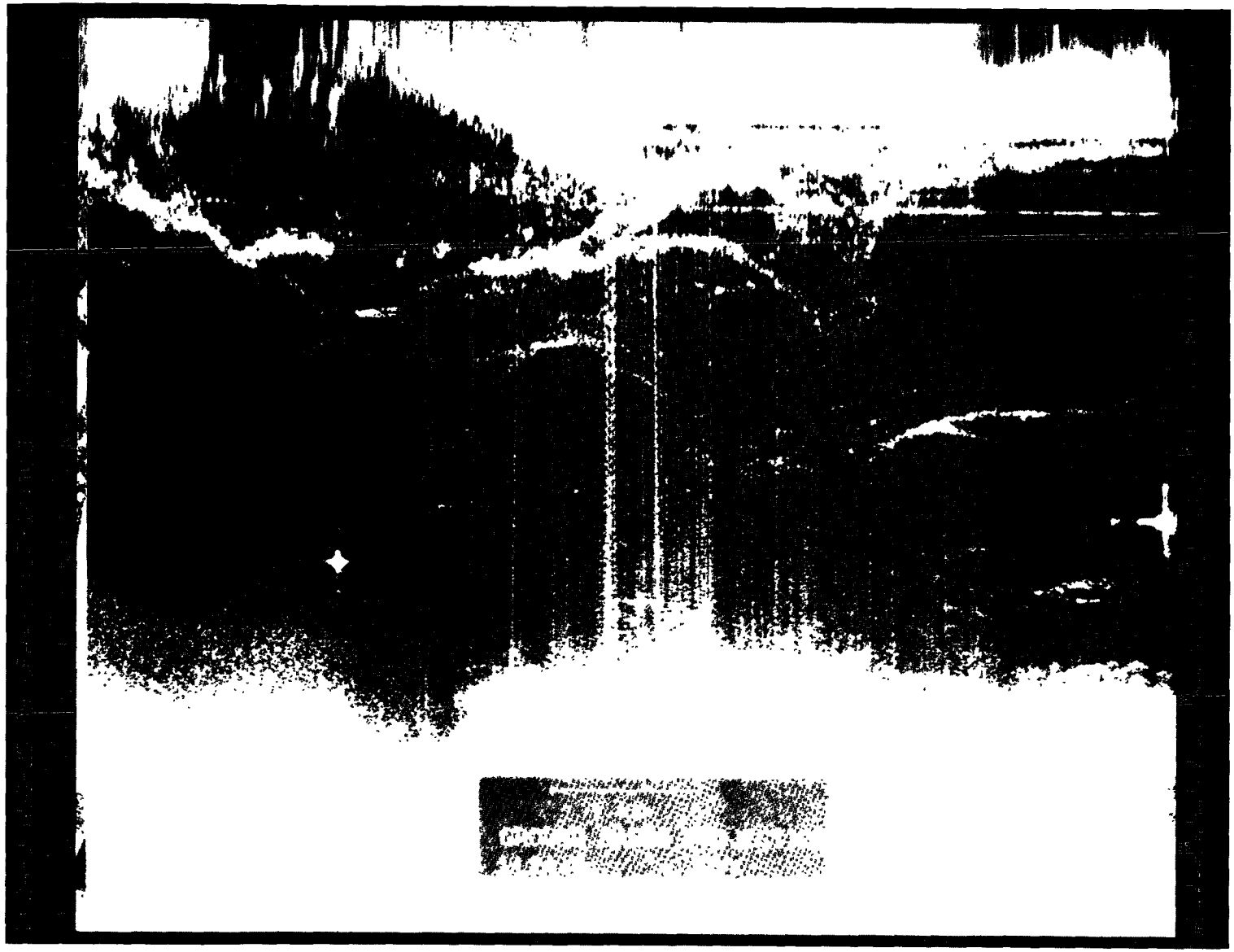

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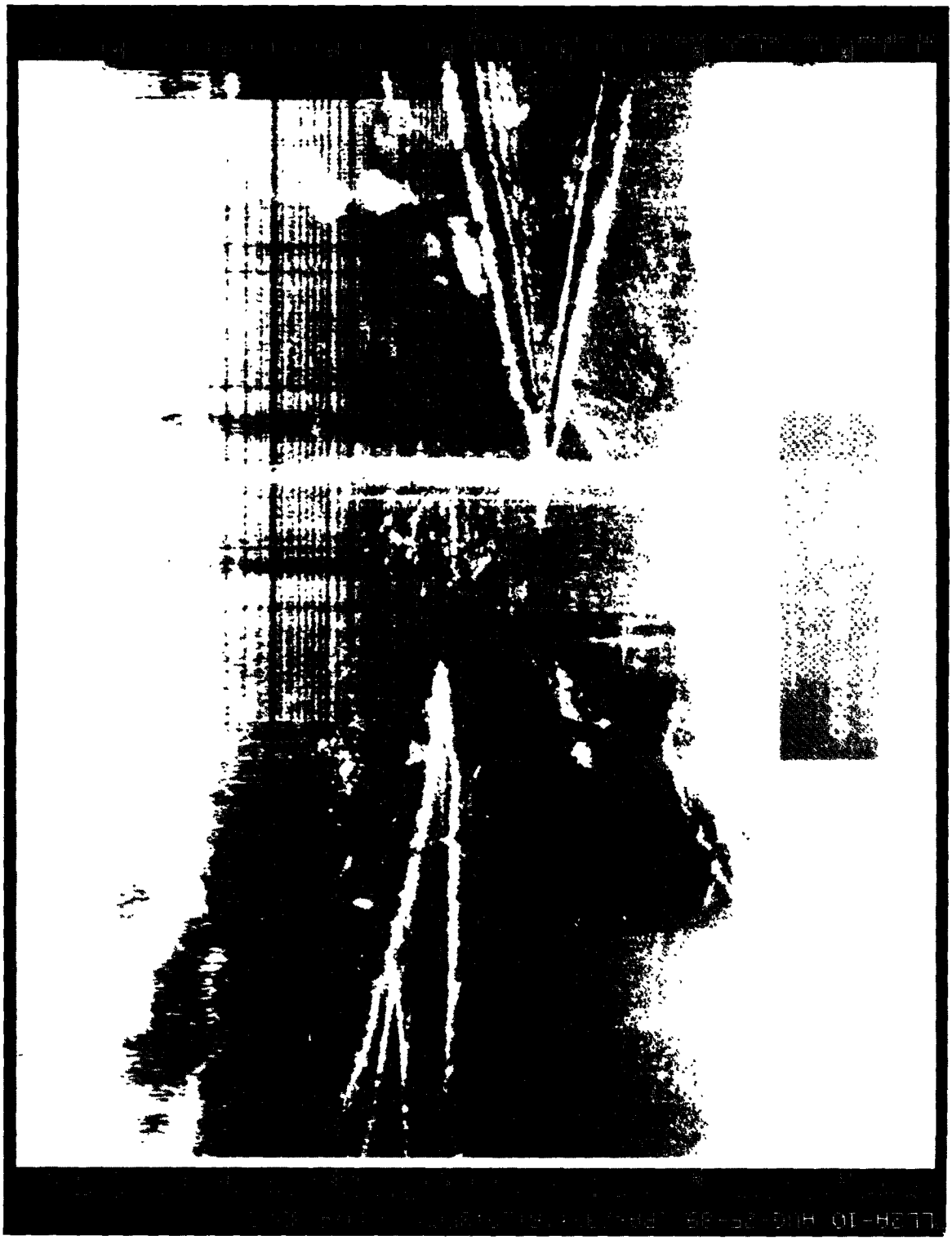

Figure A-76. August 25, 1989, Pass 10, CPA 237:16:29:35GMT LVV

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Figure A-77. August 25, 1989, Pass 11, CPA 237:16:50:33GMT LVV

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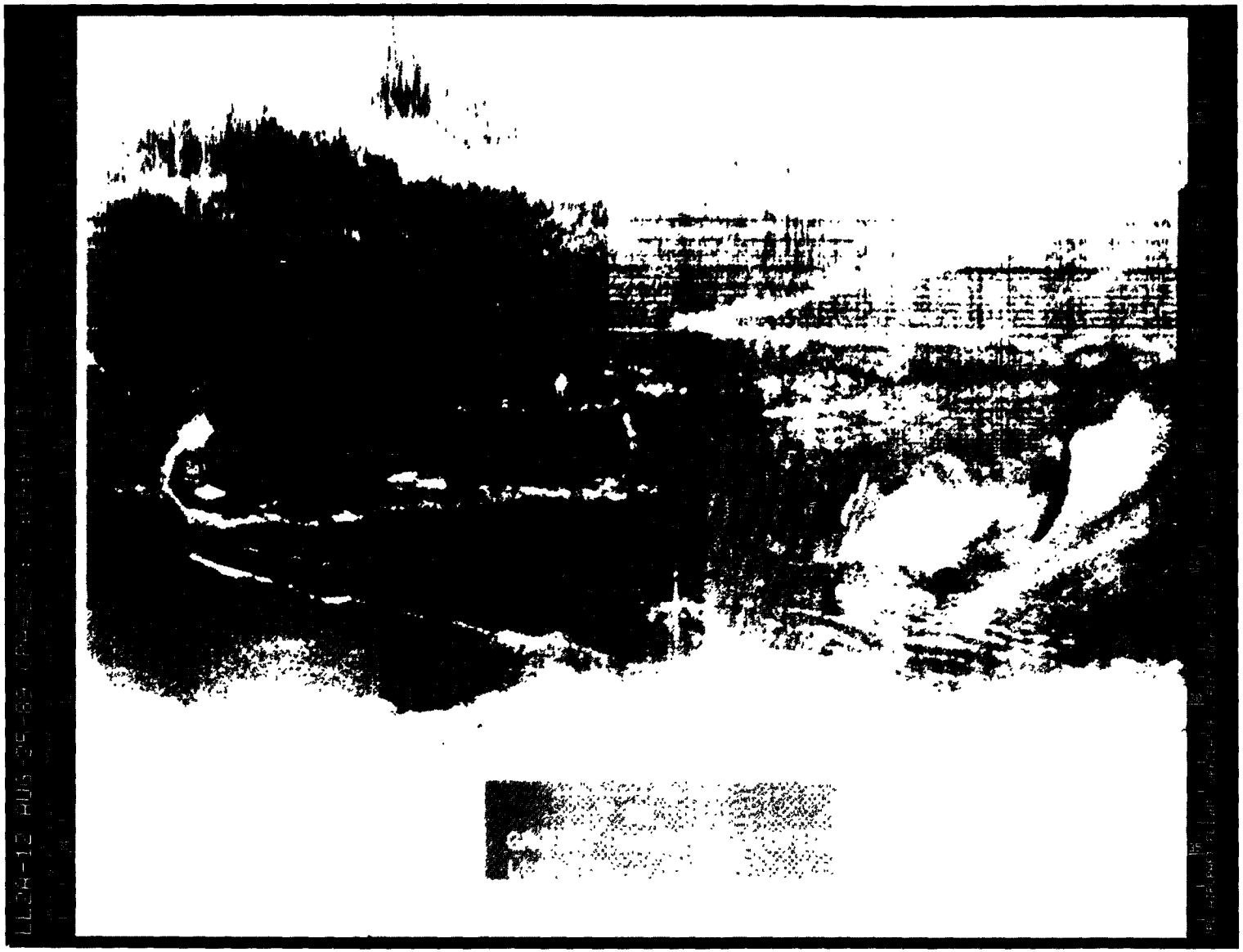

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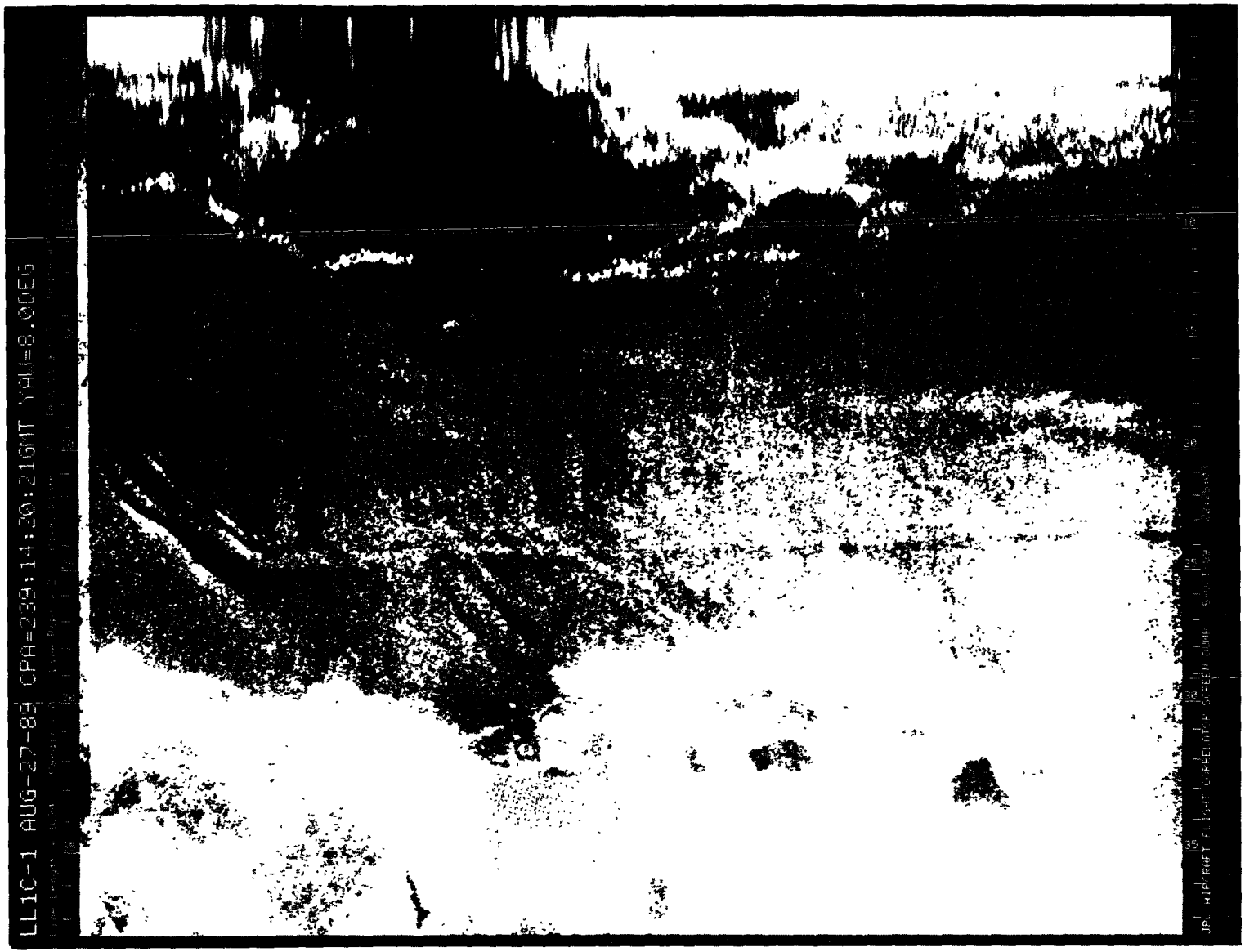

Figure A-79. August 27, 1989, Pass 1, CPA 239:14:20:21GMT PVV

Figure A-80. August 27, 1989, Pass 2, CPA 239:14:40:17GMT CVV

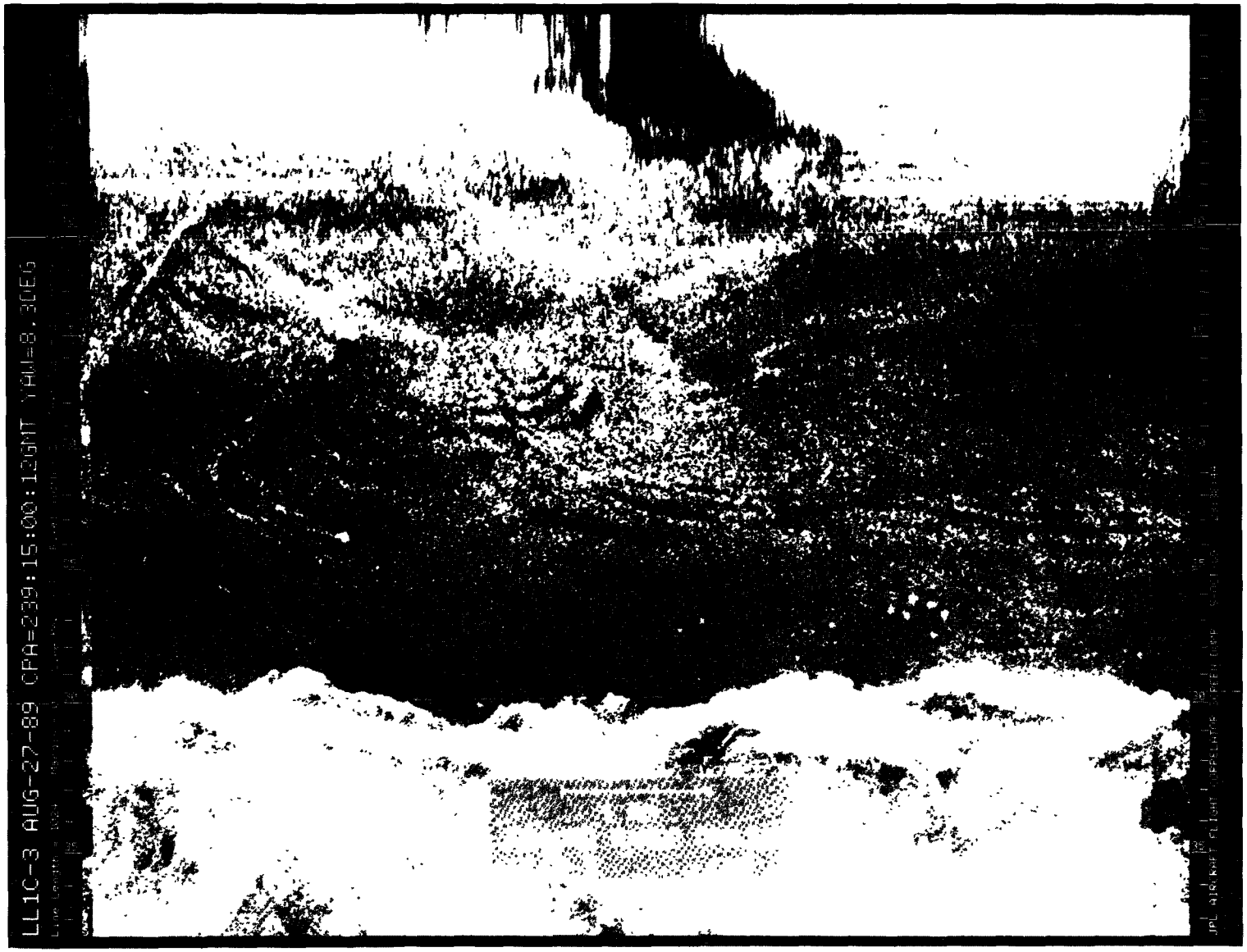

Figure A-81. August 27, 1989, Pass 3, CPA 239:15:00:12GMT LHH

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Figure A-82. August 27, 1989, Pass 4, CPA 239:15:19:39GMT LVV

Figure A-83. August 27, 1989, Pass 5, CPA 239:15:40:30GMT PVV

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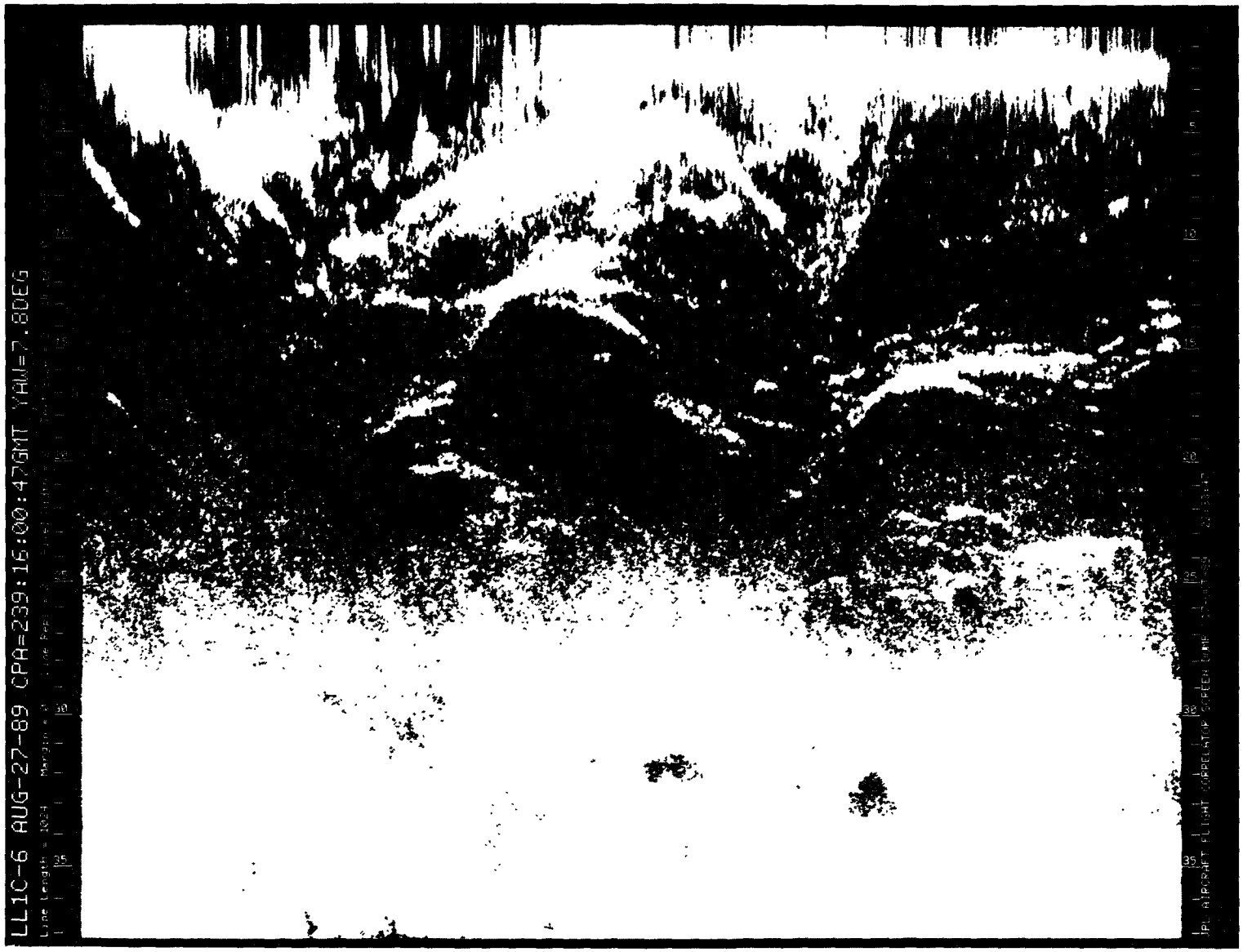

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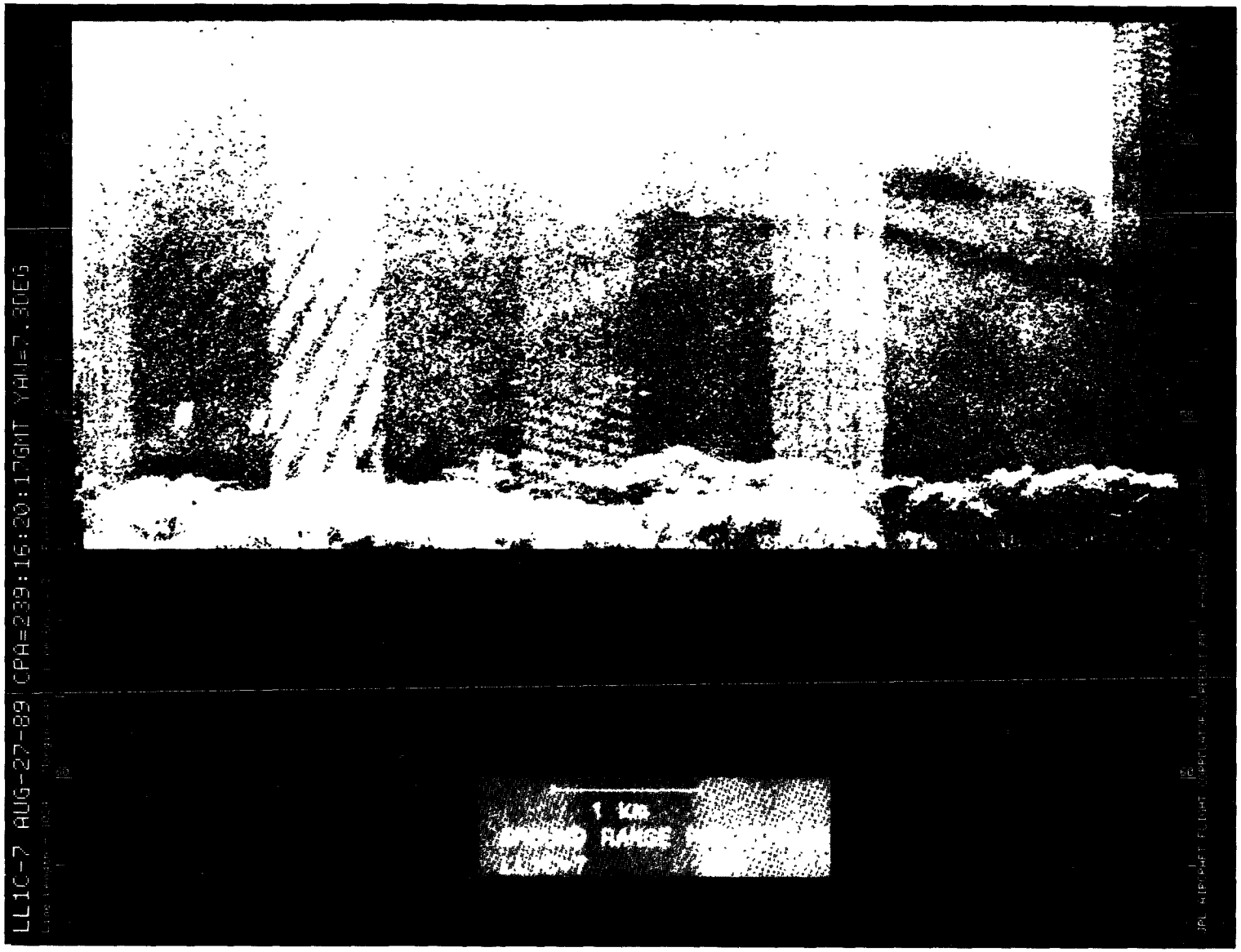

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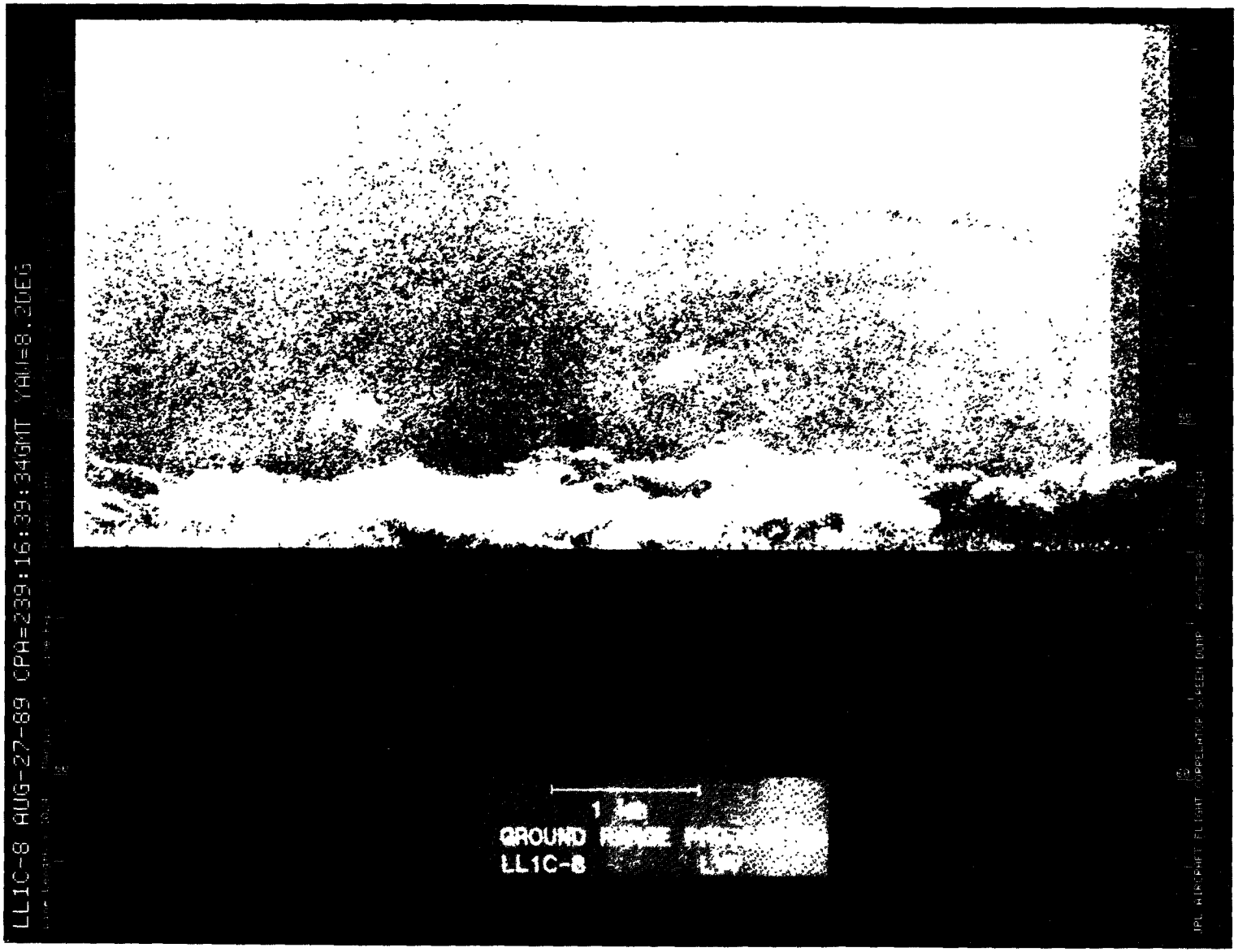

Figure A-86. August 27, 1989, Pass 8, CPA 239:16:39:34GMT LVV

Figure A-87. August 27, 1989, Pass 9, CPA 239:16:59:55GMT LVV

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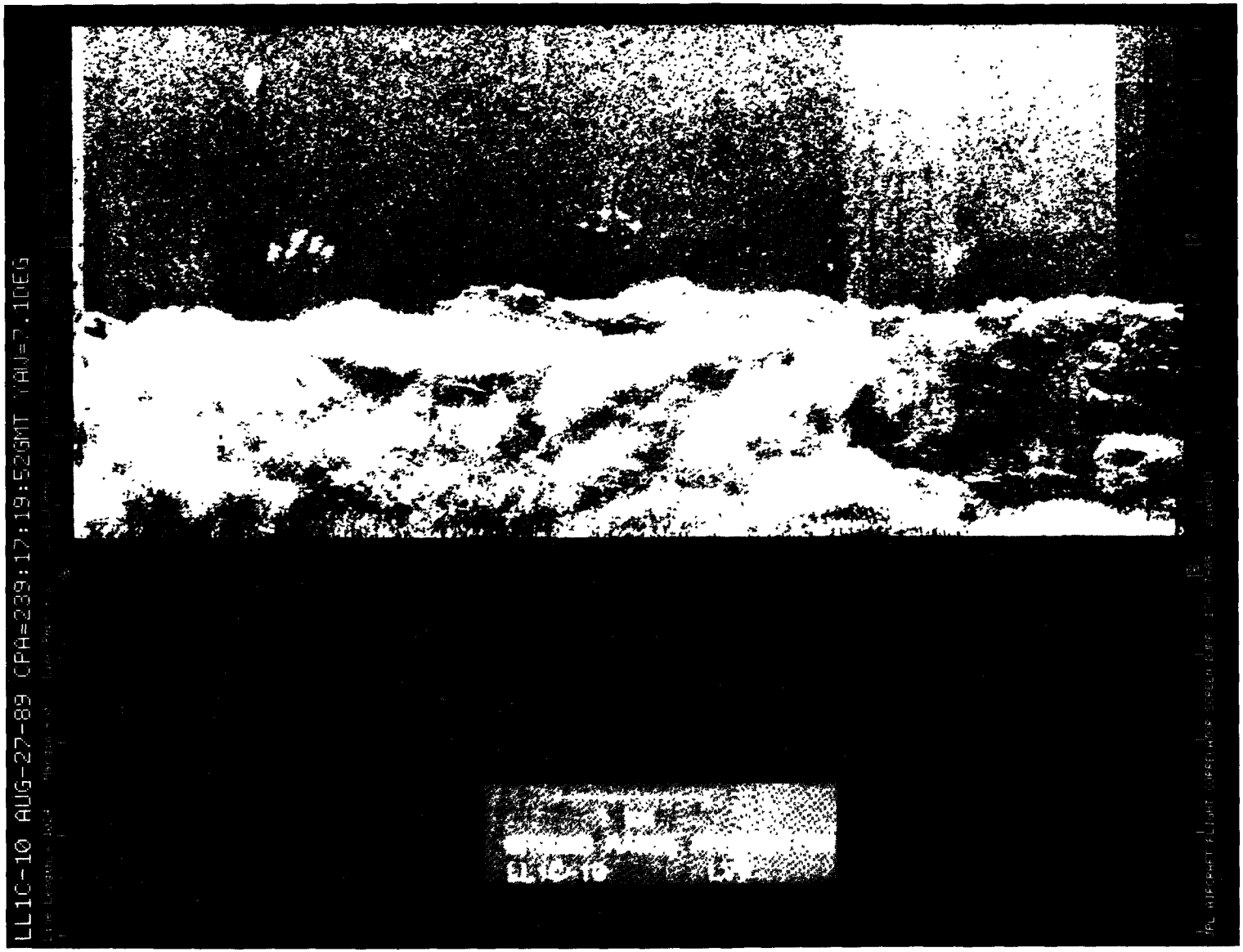

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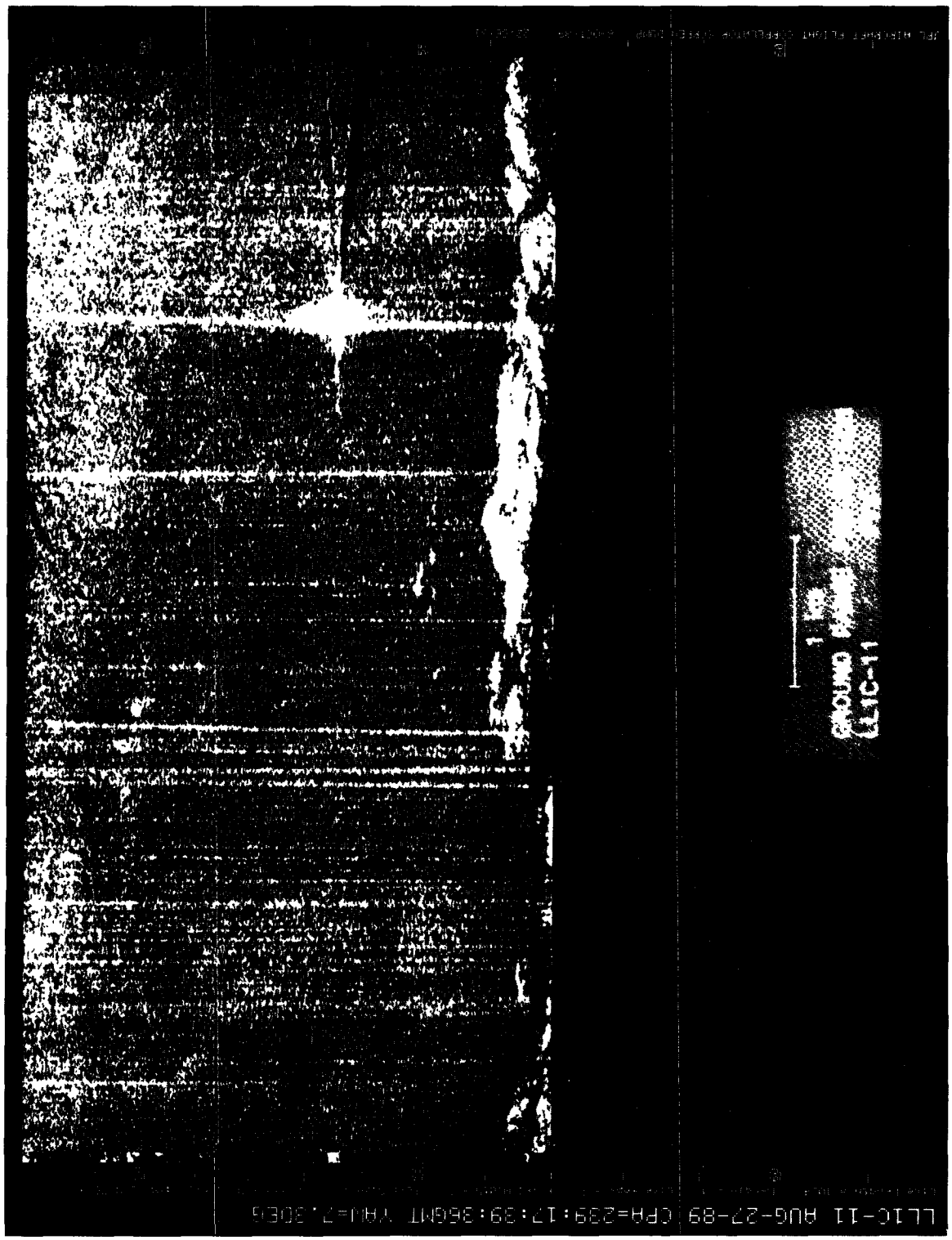

Figure A-89. August 27, 1989, Pass 11, CPA 239:17:39:36GMT PVV

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Figure A-90. August 27, 1989, Pass 12, CPA 239:18:01:03GMT PVV

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Figure A-91. August 28, 1989, Pass 1, CPA 240:14:29:57GMT LVV

Figure A-92. August 28, 1989, Pass 2, CPA 240:14:49:54GMT PVV

Figure A-93. August 28, 1989, Pass 3, CPA 240:15:10:08GMT LVV

Figure A-94. August 28, 1989, Pass 4, CPA 240:15:29:45GMT LVV

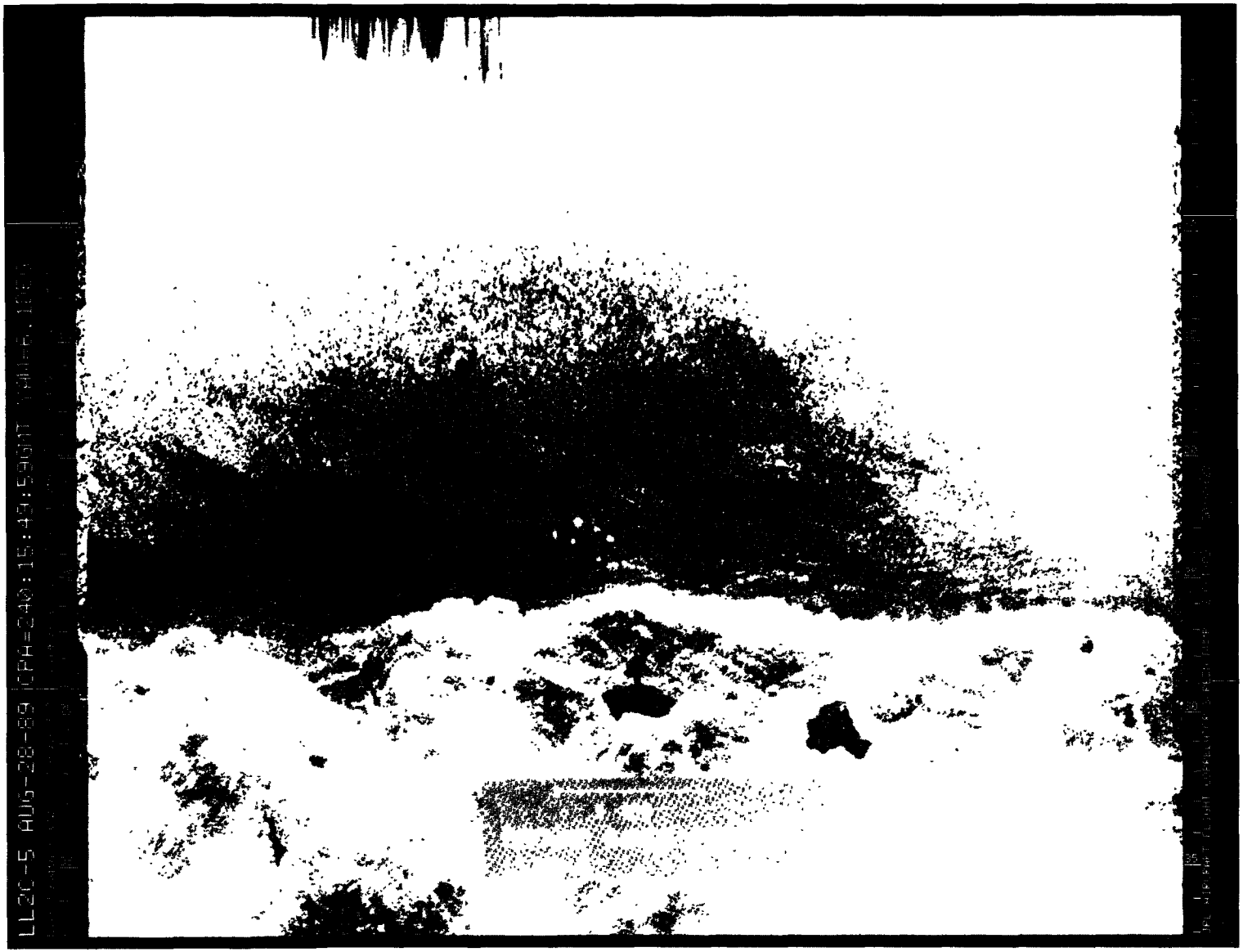
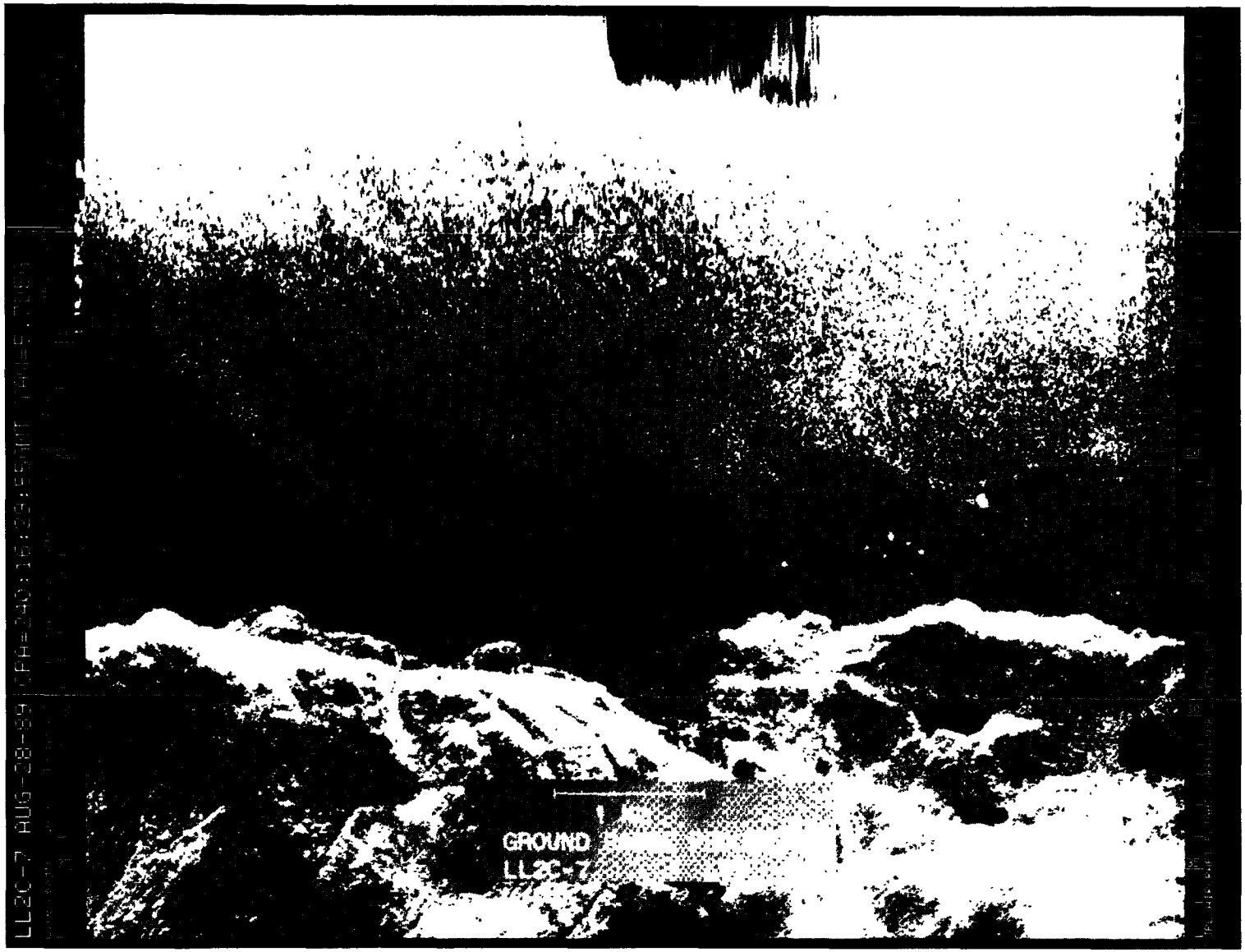


Figure A-95. August 28, 1989, Pass 5, CPA 240:15:49:59GMT LVV

Figure A-96. August 28, 1989, Pass 6, CPA 240:16:09:51GMT LVV



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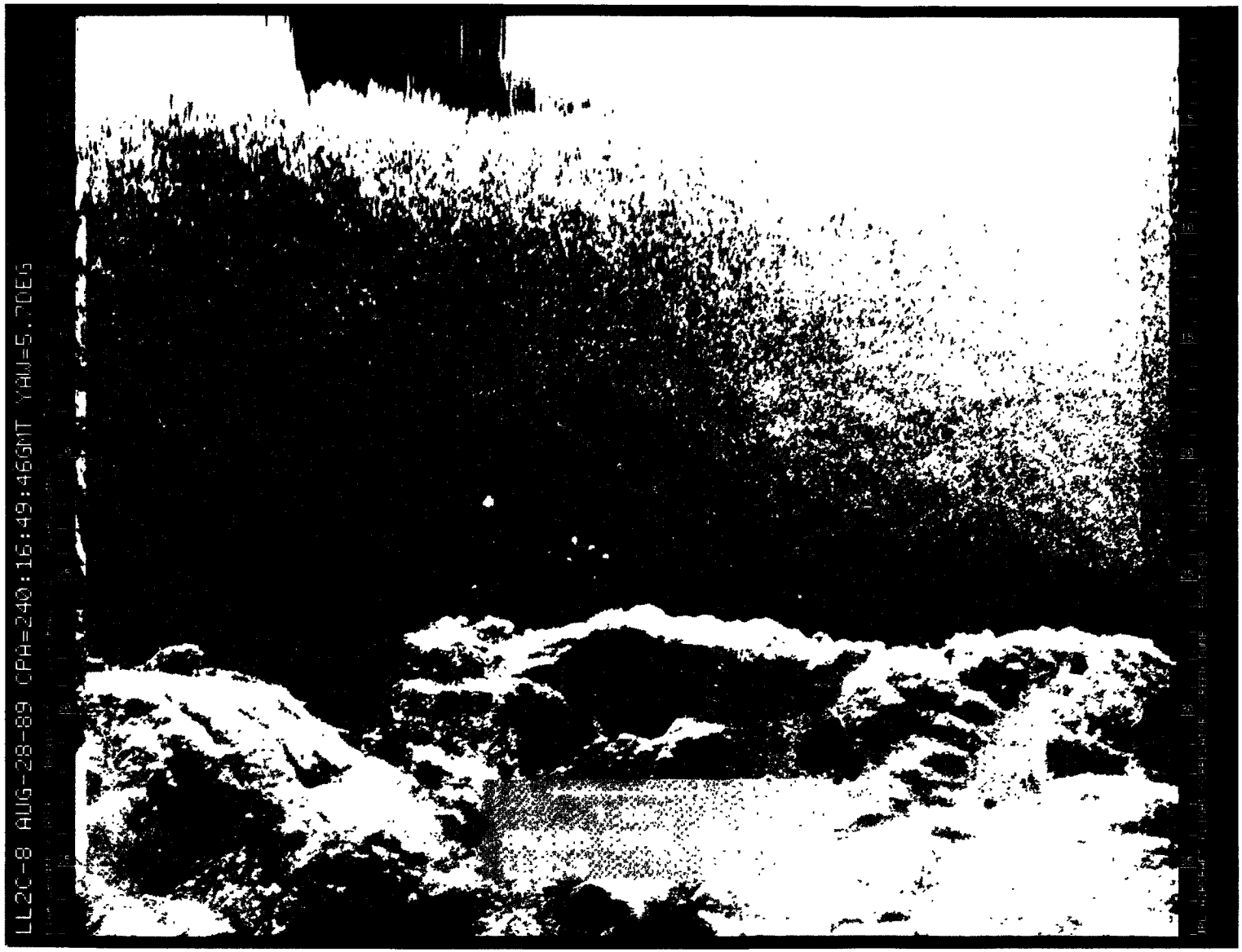

Figure A-98. August 28, 1989, Pass 8, CPA 240:16:49:46GMT LVV

Figure A-99. August 28, 1989, Pass 9, CPA 240:17:10:03GMT LVV

Figure A-100. August 28, 1989, Pass 10, CPA 240:17:30:00GMT LVV

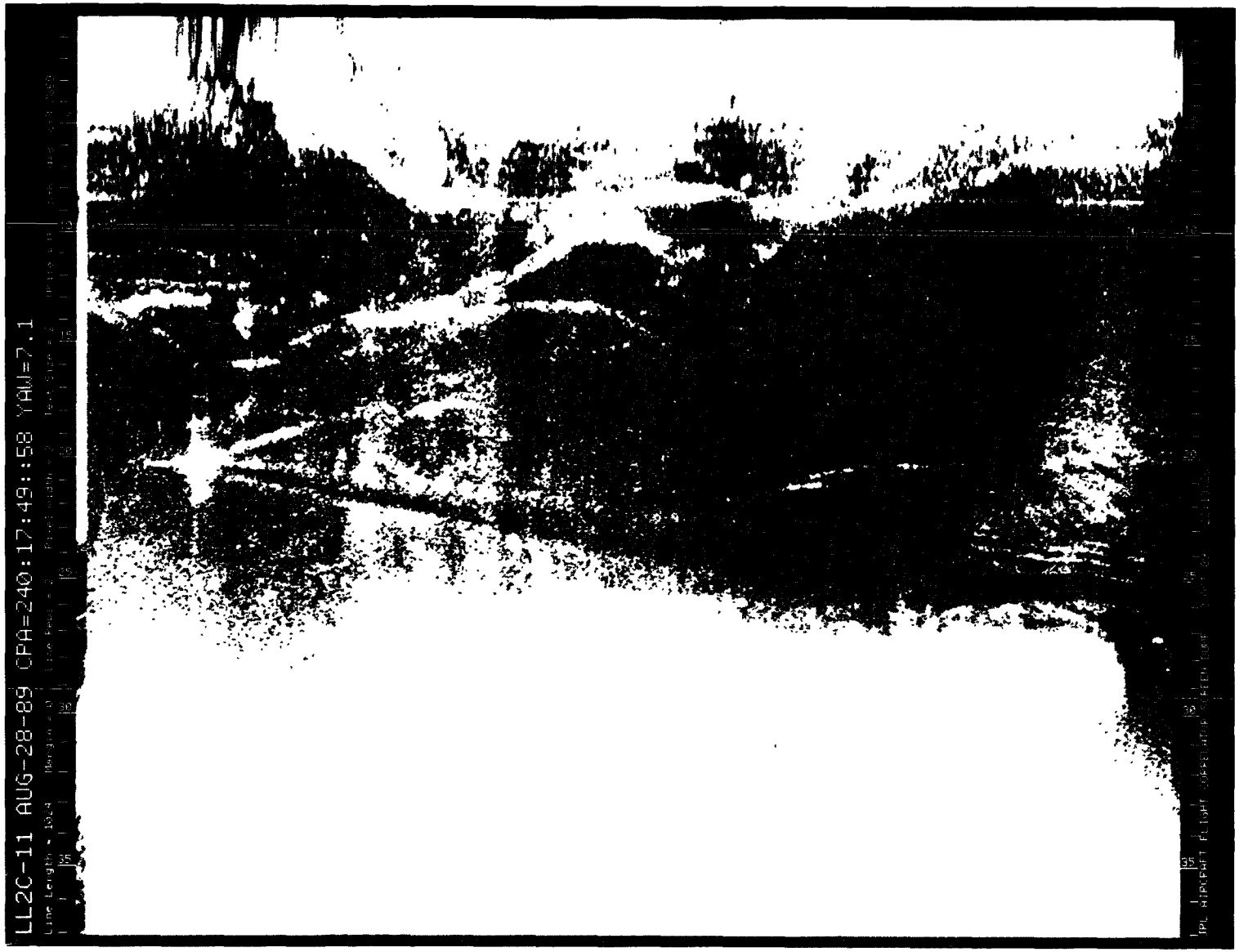

Figure A-101. August 28, 1989, Pass 11, CPA 240:17:49:58GMT PVV

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Figure A-103. August 28, 1989, Pass 11, CPA 240:17:49:58GMT CVV

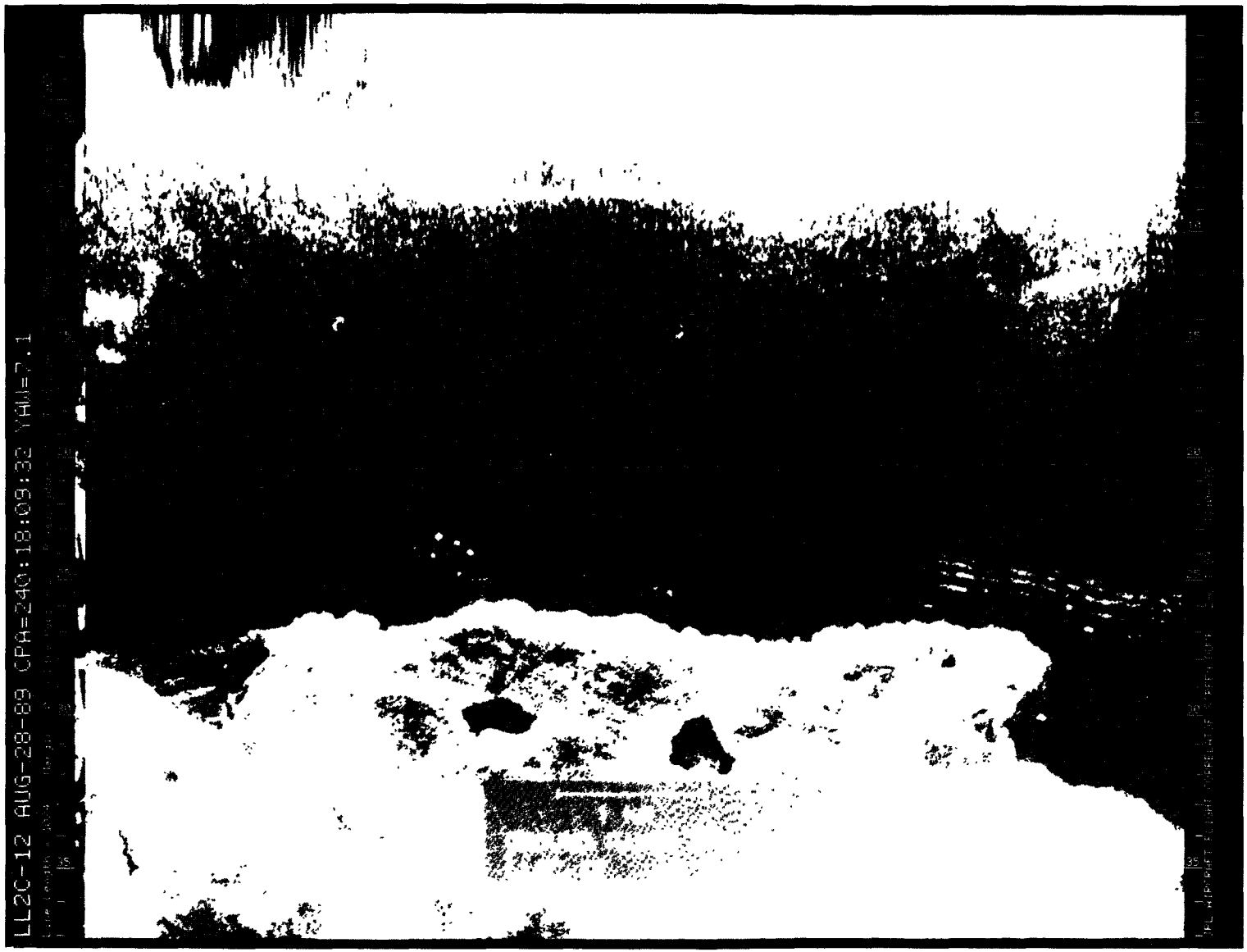

Figure A-104. August 28, 1989, Pass 12, CPA 240:18:09:32GMT LVV

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. 89-44	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle The Browse File of NASA/JPL Quick-Look Radar Images From the Loch Linnhe 1989 Experiment		5. Report Date November 15, 1989 6. Performing Organization Code
7. Author(s) Walter E. Brown, Jr., Editor		8. Performing Organization Report No.
9. Performing Organization Name and Address JET PROPULSION LABORATORY California Institute of Technology 4800 Oak Grove Drive Pasadena, California 91109		10. Work Unit No. 11. Contract or Grant No. NAS7-918 13. Type of Report and Period Covered JPL Publication
12. Sponsoring Agency Name and Address NATIONAL AERONAUTICS AND SPACE ADMINISTRATION Washington, D.C. 20546		14. Sponsoring Agency Code RE4 PP-146-07-00-00-00

15. Supplementary Notes

16. Abstract

During August of 1989, the JPL Aircraft Synthetic Aperture Radar (AIRSAR) was deployed to Scotland to obtain radar imagery of ship wakes generated in Loch Linnhe. These observations were part of a joint United States and United Kingdom experiment to study the internal waves generated by ships under partially controlled conditions. The AIRSAR was mounted on the NASA/Ames Research Center DC-8 aircraft. The data-acquisition sequence consisted of 8 flights, each about 6 hours in duration, wherein 24 observations of the instrumented site were made on each flight.

This Browse File provides the experimenters with a reference of the real-time imagery--approximately 100 images--obtained on the 38-deg track. These radar images are copies of those obtained at the time of observation and show the general geometry of the ship-wake features. To speed up processing during this flight, the images were all processed around zero Doppler, and thus azimuth ambiguities often occur when the drift angel (yaw) exceeded a few degrees. However, even with the various shortcomings, we believe the experimenter will find the Browse File useful in establishing a basis for further investigation.

17. Key Words (Selected by Author(s))	18. Distribution Statement
Physical Oceanography Radar Detection	Unclassified -- Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	130	