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TECHNICAL NOTE NO. 80-19

SEASAT EQUATOR CROSSING PROGRAM

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ABSTRACT

A programmable pocket calculator is used to extrapolate the SEASAT orbit from the equator crossing to the position at which the synthetic aperture radar images a given target. The program predicts the coordinates of the satellite at image time, the Azimuth direction of the image at the target, and the time elapsed between equator crossing and imaging. Program predictions are compared with measured SEASAT data from the definitive attitude-orbit files.

RÉSUMÉ

Ce rapport décrit le logiciel d'une calculateur de poche programmable pour l'extrapolation de l'orbite du satellite SEASAT à partir de sa traversée au-dessus de l'équateur jusqu'à sa position lorsque le radar à antenne synthétique image une cible. Ce programme permet de prévoir les coordonnées du satellite au moment de la production de l'image, la direction azimuthale de l'image au point de la cible et le temps écoulé entre le passage à l'équateur et celui de la production de l'image. Ces prédictions sont comparées avec les données mesurées de SEASAT contenues dans les fichiers à bandes magnétiques des données définitives d'attitudes et d'orbites.

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1.0 INTRODUCTION

SEASAT Equator Crossing is a program for the HP-67 hand calculator to predict when a given target will be imaged by the SEASAT synthetic aperture radar (SAR) and from what direction. The program was written and first used in the planning phase of the SURSAT Project. It helped establish surface truth procedures for the DREO experiments on the application of spaceborne SAR to the detection and classification of targets of military interest. After the launch of SEASAT the program was used in the field to update image time predictions and by the SURSAT Project Office to help select parts of the radar data records for transcription to computer compatible tapes. Recently, accurate records of the SEASAT orbit and attitude have become available and it has been possible to evaluate the program predictions.

Tables of predicted SEASAT nodes (equator crossings) and node times were published by the Jet Propulsion Laboratory (JPL) before launch and updated frequently after launch as observations accumulated. For the collection of surface truth it was necessary to extrapolate the node data to the target site with sufficient accuracy to establish the position of the target in the SAR swath, the image time, and the radar look angle. If coincident surface truth for a moving target is required the satellite can be tracked with a radar detector. A programmable pocket calculator was chosen for this task because it was anticipated that satellite orbit data and radar turn-on times might not be available until after surface truth personnel had been committed to the field.

The Seatrack calculator, designed by JPL[1] and distributed by the SURSAT Project Office to Canadian experimenters, performs essentially the same function as the SEASAT Equator Crossing program. It is more convenient to use but it is also less accurate. Time can be read to within 20 seconds and the orbit positioned to within 1/3 degree in longitude. Furthermore, point targets cannot be located with high enough precision on the small scale map base.

The present note describes the derivation and application of the SEASAT Equator Crossing program. It also assesses the validity of the approximations and assumptions by comparing SEASAT parameters predicted by the program with those extracted from the definitive attitude/orbit files.

2.0 THE SEASAT SAR MODEL

The accurate prediction of a satellite orbit is normally beyond the capacity of a pocket calculator but the SEASAT orbit was designed to be almost circular. Also the extrapolation of the orbit for this application would never exceed a quarter revolution from the nearest node.

The model for the program starts with the target position. It follows a great circle route to the satellite nadir at image time, and from there along a second great circle route to the intersection of the orbit plane with the equator at image time. Finally the node is located by accounting for earth rotation and orbit precession during the time the satellite travels from node to image point. Here nadir is the intersection of the satellite position vector with the earth's surface. The node is the point in east longitude at which the satellite crosses the equator. The design parameters shown in Table I for the SEASAT orbit were published by JPL[1] before launch in July 1978.

TABLE I

SEASAT ORBIT PARAMETERS

Eccentricity	0.0008
Inclination	108°
Period	100.75 min.

The SAR swath extends to the right of the satellite ground track from about 258 km to 358 km with the centerline at 308 km. Nominal antenna orientation is 20.5° cone and 90° clock, where the clock angle is with respect to the orbit plane.

The design eccentricity of the SEASAT orbit in Table I is small and the proposed extrapolation of the orbit beyond the node is always less than a quarter revolution, so the following simplifying assumptions can be made:

i) spherical earth
ii) circular SEASAT orbit
iii) side-looking attitude

With these assumptions, a path on the surface of the rotating spherical earth was traced iteratively from the target to the spacecraft nadir at image time and from there to the node at node time.

Let the target of interest have geocentric latitude L_1 and longitude λ_1. The coordinates of the satellite nadir at the time the target is centered in the radar beam are L_2 and λ_2. The great circle navigation equations from the HP-67 users library were recast as relations (1), (2) and (3) to express L_2 and λ_2 as functions of L_1, λ_1, the angular distance D/60 between the target and satellite, and the heading H from target to satellite. H is not known at this stage. It is given the initial value 185° for the ascending leg (a) and 175° for the descending leg (d) to place the satellite in the correct quadrant relative to the target. Although the final values of H are different for ascending and descending legs, from symmetry L_2 is independent of H and only one equation is shown.

$$L_2 = \sin^{-1}[\cos H \sin (D/60) \cos L_1 + \sin L_1 \cos (D/60)] \ . \qquad (1)$$

$$\lambda_2(a) = \lambda_1 + \cos^{-1} \left[\frac{\cos(d/60) - \sin L_1 \sin L_2}{\cos L_1 \cos L_2}\right]. \qquad (2)$$

$$\lambda_2(d) = \lambda_1 - \cos^{-1} \left[\frac{\cos(d/60) - \sin L_1 \sin L_2}{\cos L_1 \cos L_2}\right]. \qquad (3)$$

The equator crossing point E_{cross} for an orbit over (L_2, λ_2) was calculated in three steps. First, the intersection of the SEASAT orbit plane through L_2, λ_2 with the equator was found from the right spherical triangle ABC in Figure 1 (ascending leg only shown). Here C = 90°, B = 72° (inclination 108°), b = L_2, and

$$A = \sin^{-1}\left[\frac{\sin(90-B)}{\cos L_2}\right], \tag{4}$$

$$a = \cos^{-1}\left[\frac{\cos A}{\cos(90-B)}\right], \tag{5}$$

$$c = \cos^{-1}[\cos a \cos L_2]. \tag{6}$$

Next, the time elapsed between the satellite crossing of the equator and target illumination by the radar, T_{lapse}, was found from the orbit period T by Equation (7). Note that T_{lapse} is independant of earth rotation.

$$T_{lapse} = [T/360]c \, . \tag{7}$$

The shift a^1 in the equator crossing point due to earth rotation rate W and orbit precession rate Ω during T_{lapse} is

$$a^1 = T_{lapse}(W - \Omega)/(24 \times 60), \tag{8}$$

where W = 360.9856474 deg/day and Ω = 2.0459358 deg/day [1].

Finally, the equator crossing point, E_{cross}, in degrees east longitude is

$$E_{cross}(a) = 360 - \lambda_2\ (a) + a + a^1 , \tag{9}$$

$$E_{cross}(d) = 360 - \lambda_2\ (d) - a - a^1 . \tag{10}$$

E_{cross} is the program prediction for the node but the term will be retained to identify source of data.

At the end of this first iteration a refined direction H from target to satellite nadir was determined by recalling that the radar antenna has a 90° clock angle with respect to the satellite orbit plane. This was done in three stages. First, the heading H_o from the satellite nadir at (L_2, λ_2) to the target at (L_1, λ_1) was calculated from the great circle navigation relation given in (11). Second, the difference ΔH between the headings at each end of the great circle segment (L_2, λ_2) to (L_1, λ_1) was found by equation (12) for the ascending leg, and by equation (13) for the descending leg.

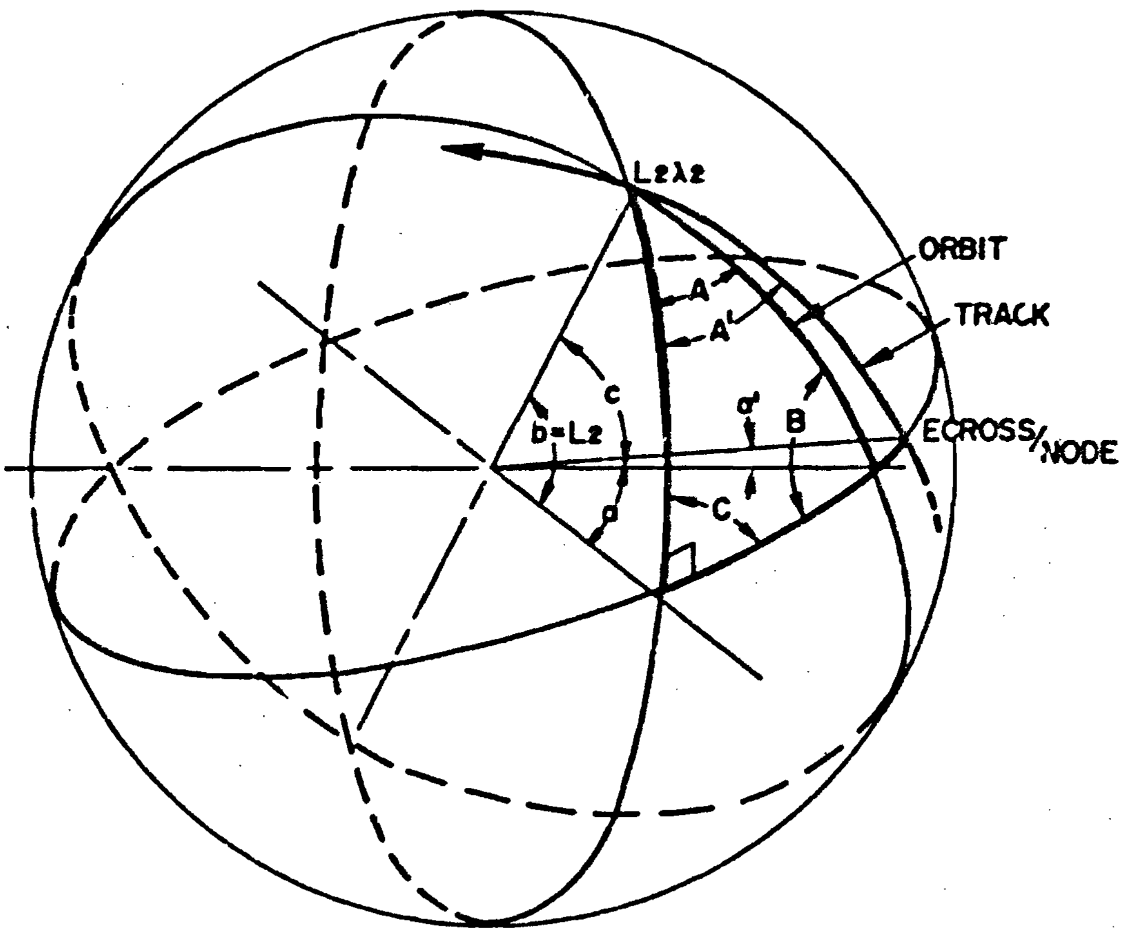

FIGURE 1 - RIGHT SPHERICAL TRIANGLE ABC FOR ASCENDING NODE.

Finally, new values of H were calculated by relations (14) and (15).

$$H_o = \cos^{-1}\left[\frac{\sin L_1 - \cos(D/60) \sin L_2}{\sin(D/60) \cos L_2}\right] . \quad (11)$$

$$\Delta H(a) = H - (H_o + 180) . \quad (12)$$

$$\Delta H(d) = H + H_o - 180 . \quad (13)$$

$$H(a) = \Delta H(a) + 270 - A . \quad (14)$$

$$H(d) = \Delta H(d) + 90 + A . \quad (15)$$

The relationships among these parameters for ascending and descending legs are shown schematically in the plan view of Figure 2.

Two useful numbers are the satellite ground track heading and the cross range SAR swath heading through the target at image time. These are found in equations (16) to (19) by adding the earth rotation and satellite angular velocities and converting from one to the other using ΔH.

$$A^1 = \tan^{-1}\left[\frac{1}{\cos A} (\sin A + K \cos L_2)\right] . \quad (16)$$

where $K = \frac{T}{360} \left(\frac{W - \Omega}{24 \times 60}\right)$,

$$\text{SEASAT Heading (a)} = 360 - A^1 , \quad (17)$$

$$\text{SEASAT Heading (d)} = 180 + A^1 , \quad (18)$$

$$\text{SAR Swath Heading} = \text{SEASAT Heading} + \Delta H . \quad (19)$$

3.0 THE CALCULATOR PROGRAM

Instructions for entering the program and the data are given in Table II. The program itself is listed in Table III for the ascending leg and in Table IV for the descending leg.

The SEASAT SAR model was based on a spherical earth and geocentric coordinates whereas the real earth is more closely approximated by an oblate ellipsoid of eccentricity e = 0.08199189. The geographic latitude, LAT, which is defined by the normal to the ellipsoid and is used in mapping, can be converted to the geocentric latitude L [2] by

$$L = \tan^{-1}[(1-e^2) \tan LAT]. \quad (20)$$

The error introduced by using the geographic latitude instead of the geocentric latitude is negligible at the equator and the poles but reaches 11.6' at 45°. Latitude and longitude are entered conventionally in the program as degrees · minutes seconds. For example, 130.5732 means

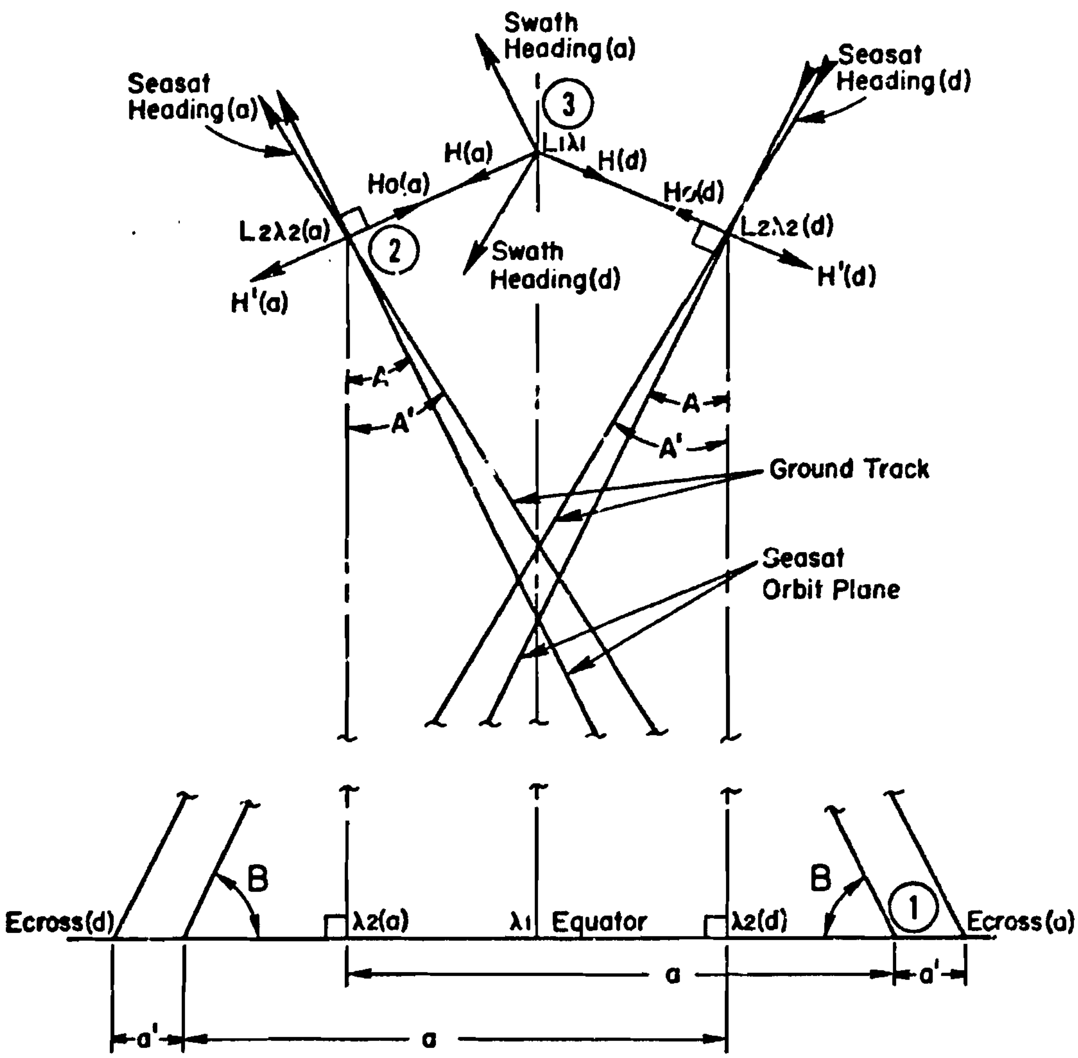

FIGURE 2 - SEASAT SAR GEOMETRY.

TABLE II

User Instructions

7

SEASAT Equator Crossing a (ascending) d (descending) 3/80

1 | 2

L_1 | λ_1 | E_{cross} | T_{lapse} | Heading

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Enter program, both sides				
2	Enter latitude of target *	L_1	A		6.0 (I)
3	Change I?	I	h	STI	
4	Change D/60? (nm/min)	D/60	STO	6	
5	Change inclination? (dec. deg)	90-B	STO	7	
6	Change T/360? (min/deg)	T/360	STO	8	
7	Enter longitude of target * (W)	λ_1	B		
8	Calculate SEASAT equator crossing (E. Long)		C		E_{cross}
9	Calculate time in minutes between equator crossing and target imaging		D		T_{lapse}
10	Calculate heading of SAR swath at target		E		Swath Heading
	* Enter lat. and long. in the form DDD.MMSS eg. 130.5732 means 130 degrees, 57 minutes, 32 seconds				

TABLE III

PROGRAM LISTING, ASCENDING (a)

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
001	LBL A	31 25 11			LBL B	31 25 12	
	DSP 4	23 04			H ←	31 74	
	H ←	31 74			STO 2	33 02	λ_1
	STO 1	33 01	L_1	060	RTN	35 22	
	2	02			LBL E	31 25 15	
	.	83			P/S	31 42	
	7	07			RCL 6	34 06	
	7	07			P/S	31 42	
	1	01			RTN	35 22	
010	7	07			LBL D	31 25 14	
	7	07			P/S	31 42	
	8	08			RCL 1	34 01	
	2	02			P/S	31 42	
	5	05		070	RTN	35 22	
	8	08			LBL C	31 25 13	
	STO 6	33 06	D/60		RCL 1	34 01	
	1	01			COS	31 63	
	8	08			RCL 6	34 06	
	.	83			SIN	31 62	
020	0	00			x	71	
	0	00			RCL 5	34 05	
	0	00			COS	31 63	
	0	00			x	71	
	0	00		080	RCL 6	34 06	
	0	00			COS	31 63	
	0	00			RCL 1	34 01	
	STO 7	33 07	90-B		SIN	31 62	
	.	83			x	71	
	2	02			+	61	
030	4	04			SIN^{-1}	32 62	
	9	09			STO 3	33 03	L_2
	2	02			SIN	31 62	
	6	06			RCL 1	34 01	
	3	03		090	SIN	31 62	
	6	06			x	71	
	8	08			RCL 6	34 06	
	9	09			COS	31 63	
	STO 9	33 09	(W − Ω)/(24 x 60)		−	51	
	.	83			CHS	42	
040	2	02			RCL 1	34 01	
	7	07			COS	31 63	
	9	09			RCL 3	34 03	
	8	08			COS	31 63	
	6	06		100	x	71	
	1	01			÷	81	
	1	01			COS^{-1}	32 63	
	1	01			RCL 2	34 02	
	1	01			+	61	
	STO 8	33 08	T/360		STO 4	33 04	λ_2
050	1	01			3	03	
	8	08			6	06	
	5	05			0	00	
	STO 5	33 05	H initial		−	51	
	6	06		110	CHS	42	
	STI	35 33			P/S	31 42	
	RTN	35 22			STO 8	33 08	

REGISTERS

0 a	1 L_1	2 λ_1	3 L_2	4 λ_2	5 H	6 D/60	7 90-B	8 T/360	9 $\frac{W - \Omega}{24 \times 60}$
S0 H^1	S1 T_{lapse}	S2 $a + a^1$	S3 H_o	S4 SEASAT Heading	S5 ΔH	S6 Swath Heading	S7	S8 E_{cross}	S9

A L_1	B λ_1	C E_{cross}	D T_{lapse}	E Swath Heading	I 6

TABLE III (cont'

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
	P/S	31 42			STO 3	33 03	H_o
	RCL 7	34 07		170	P/S	31 42	
	SIN	31 62			1	01	
	RCL 3	34 03			8	08	
	COS	31 63			0	00	
	÷	81			+	61	
	SIN^{-1}	32 62	A		RCL 5	34 05	
120	2	02			-	51	
	7	07			CHS	42	
	0	00			P/S	31 42	
	-	51			STO 5	33 05	
	CHS	42		180	RCL 0	34 00	
	P/S	31 42			P/S	31 42	
	STO 0	33 00	H^1		+	61	
	P/S	31 42			STO 5	33 05	H
	SIN	31 62			RCL 3	34 03	
	CHS	42			COS	31 63	
130	RCL 7	34 07			RCL 8	34 08	
	COS	31 63			X	71	
	÷	81			RCL 9	34 09	
	COS^{-1}	32 63			X	71	
	STO 0	33 00	a	190	P/S	31 42	
	COS	31 63			RCL 0	34 00	
	RCL 3	34 03			COS	31 63	
	COS	31 63			-	51	
	X	71			CHS	42	
	COS^{-1}	32 63	c		RCL 0	34 00	
140	RCL 8	34 08			SIN	31 62	
	X	71			÷	81	
	P/S	31 42			TAN^{-1}	32 64	A^1
	STO 1	33 01	T_{lapse}		3	03	
	P/S	31 42		200	6	06	
	RCL 9	34 09			0	00	
	X	71			-	51	
	RCL 0	34 00			CHS	42	
	+	61			STO 4	33 04	SEASAT Heading
	P/S	31 42			RCL 5	34 05	
150	STO 2	33 02	$n + a^1$		+	61	
	STO + 8	33 61 08	E_{cross}		STO 6	33 06	Swath Heading
	P/S	31 42			P/S	31 42	
	RCL 1	34 01			DSZ	31 33	
	SIN	31 62		210	GTO C	22 13	
	RCL 6	34 06			P/S	31 42	
	COS	31 63			RCL 8	34 08	E_{cross}
	RCL 3	34 03			P/S	31 42	
	SIN	31 62			RTN	35 22	
	X	71					
160	-	51					
	RCL 6	34 06					
	SIN	31 62					
	RCL 3	34 03					
	COS	31 63		220			
	X	71					
	÷	81					
	COS^{-1}	32 63					
	P/S	31 42					

LABELS					FLAGS
A L_1	B λ_1	C E_{cross}	D T_{lapse}	E Swath Heading	0
a	b	c	d	e	1
0	1	2	3	4	2
5	6	7	8	9	3

SET STATUS		
FLAGS	TRIG	DISP 4
ON OFF		
0 [ ] [ ]	DEG [ ]	FIX [ ]
1 [ ] [ ]	GRAD [ ]	SCI [ ]
2 [ ] [ ]	RAD [ ]	ENG [ ]
3 [ ] [ ]		n____

TABLE IV

PROGRAM LISTING, DESCENDING (d)

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
001	LBL A	31 25 11			LBL B	31 25 12	
	DSP 4	23 04			H ←	31 74	
	H ←	31 74			STO 2	33 02	λ_1
	STO 1	33 01	L_1	060	RTN	35 22	
	2	02			LBL E	31 25 15	
	.	83			P/S	31 42	
	7	07			RCL 6	34 06	
	7	07			P/S	31 42	
	1	01			RTN	35 22	
010	7	07			LBL D	31 25 14	
	7	07			P/S	31 42	
	8	08			RCL 1	34 01	
	2	02			P/S	31 42	
	5	05		070	RTN	35 22	
	8	08			LBL C	31 25 13	
	STO 6	33 06	D/60		RCL 1	34 01	
	1	01			COS	31 63	
	8	08			RCL 6	34 06	
	.	83			SIN	31 62	
020	0	00			X	71	
	0	00			RCL 5	34 05	
	0	00			COS	31 63	
	0	00			X	71	
	0	00		080	RCL 6	34 06	
	0	00			COS	31 63	
	0	00			RCL 1	34 01	
	STO 7	33 07	90-B		SIN	31 62	
	.	83			X	71	
	2	02			+	61	
030	4	04			SIN^{-1}	32 62	
	9	09			STO 3	33 03	L_2
	2	02			SIN	31 62	
	6	06			RCL 1	34 01	
	3	03		090	SIN	31 62	
	6	06			X	71	
	8	08			RCL 6	34 06	
	9	09			COS	31 63	
	STO 9	33 09	(W - Ω)/(24 x 60)		-	51	
	.	83			CHS	42	
040	2	02			RCL 1	34 01	
	7	07			COS	31 63	
	9	09			RCL 3	34 03	
	8	08			COS	31 63	
	6	06		100	X	71	
	1	01			÷	81	
	1	01			COS^{-1}	32 63	
	1	01			RCL 2	34 02	
	1	01			-	51	
	STO 8	33 08	T/360		CHS	42	
050	1	01			STO 4	33 04	λ_2
	2	02			3	03	
	5	05			6	06	
	STO 5	33 05	H initial		0	00	
	6	06		110	-	51	
	STI	35 33			CHS	42	
	RTN	33 22			P/S	31 42	

REGISTERS

0	1	2	3	4	5	6	7	8	9
a	L_1	λ_1	L_2	λ_2	H	D/60	90 - B	T/360	$\frac{W - \Omega}{24 \times 60}$
S0 H^1	S1 T_{lapse}	S2 $a + a^1$	S3 $360 - H_o$	S4 Seasat Heading	S5 ΔH	S6 Swath Heading	S7	S8 E_{cross}	S9

A	B	C	D	E	I
L_1	λ_1	E_{cross}	T_{lapse}	Swath Heading	

TABLE IV (cont'd)

STEP	KEY ENTRY	KEY CODE	COMMENTS
	STO 8	33 08	
	P/S	31 42	
	RCL 7	34 07	
	SIN	31 62	
	RCL 3	34 03	
	COS	31 63	
	÷	81	
120	SIN^{-1}	32 62	
	9	09	
	0	00	
	+	61	
	P/S	31 42	
	STO 0	33 00	H^1
	P/S	31 42	
	SIN	31 62	
	RCL 7	34 07	
	COS	31 63	
130	÷	81	
	COS^{-1}	32 63	
	STO 0	33 00	a
	COS	31 63	
	RCL 3	34 03	
	COS	31 63	
	X	71	
	COS^{-1}	32 63	c
	RCL 8	34 06	
	X	71	
140	P/S	31 42	
	STO 1	33 01	T_{lapse}
	P/S	31 42	
	RCL 9	34 09	
	X	71	a^1
	RCL 0	34 00	
	+	61	
	P/S	31 42	
	STO 2	33 02	$a + a^1$
	STO − 8	33 51 08	E_{cross}
150	P/S	31 42	
	RCL 1	34 01	
	SIN	31 62	
	RCL 6	34 06	
	COS	31 63	
	RCL 3	34 03	
	SIN	31 62	
	X	71	
	−	51	
	RCL 6	34 06	
160	SIN	31 62	
	RCL 3	34 03	
	COS	31 63	
	X	71	
	÷	81	
	COS^{-1}	32 63	
	P/S	31 42	
	STO 3	33 03	H_o $(360 - H_o)$
	P/S	31 42	

STEP	KEY ENTRY	KEY CODE	COMMENTS 13 B
	RCL 5	34 05	
170	+	61	
	1	01	
	8	08	
	0	00	
	−	51	
	P/S	31 42	
	STO 5	33 05	ΔH
	RCL 0	33 00	
	P/S	31 42	
	+	61	
180	STO 5	33 05	H
	RCL 3	34 03	
	COS	31 63	
	RCL 8	34 08	
	X	71	
	RCL 9	34 09	
	X	71	
	P/S	31 42	
	RCL 0	34 00	
	COS	31 63	
190	−	51	
	CHS	42	
	RCL 0	34 00	
	SIN	31 62	
	÷	81	
	CHS	42	
	TAN^{-1}	32 64	A^1
	1	01	
	8	08	
	0	00	
200	+	61	
	STO 4	33 04	SEASAT Heading
	RCL 5	34 05	
	+	61	
	STO 6	33 06	Swath Heading
	P/S	31 42	
	DSZ	31 33	
	GTO C	22 13	
	P/S	31 42	
	RCL 8	34 08	E_{cross}
210	P/S	31 42	
	RTN	35 22	
220			

LABELS

A L_1	B λ_1	C E_{cross}	D T_{lapse}	E Swath Heading
a	b	c	d	e
0	1	2	3	4
5	6	7	8	9

FLAGS

0
1
2
3

SET STATUS

FLAGS ON OFF	TRIG	DISP 4
0 [ ] [ ]	DEG [ ]	FIX [ ]
1 [ ] [ ]	GRAD [ ]	SCI [ ]
2 [ ] [ ]	RAD [ ]	ENG [ ]
3 [ ] [ ]		n ____

TABLE VI

TEST OUTPUT FOR HALIFAX CITADEL

Program Title SEASAT Equator Crossing

Name B.G. Young and D.L. Desaulniers **Date** April 1980

Address

City **State** **Zip Code**

Program Description, Equations, Variables, etc.

Geocentric Coordinates: 44° 27' 24" N, 63° 35' W, I = 6

	Register	ascending (a)	descending (d)
E_{cross}	S_8	313.9726	278.8607
T_{lapse}	S_1	12.9246	12.9246
Swath H	S_6	334.7237	205.2763
L_2	R_3	43.3323	43.3323
λ_2	R_4	67.0996	60.0671
H	R_5	247.2984	112.7016
a_1	R_0	17.8506	17.8506
H^1	S_0	244.8599	115.1401
$a + a^1$	S_2	21.0722	21.0722
$H_o/(360-H_o)$	S_3	64.8599	64.8599
SEASAT H	S_4	332.2853	207.7147
ΔH	S_5	2.4384	- 2.4384

Units are decimal degrees except for T_{lapse} in decimal minutes

Operating Limits and Warnings

130 degrees, 57 minutes, and 32 seconds. The default values of the constants in the program are listed in Table V.

TABLE V

PROGRAM CONSTANTS

I(number of iterations)	6
D/60 (nautical miles/minutes)	2.771778258°
90-B (decimal degrees)	18.0000000°
T/360 (minutes/degrees)	0.279861111
(W - [illegible])/(24 x 60)	0.249263689
H(a) (initial)	185°
H(d) (initial)	175°

Six iterations were chosen to ensure convergence of all of the program output data to four decimal places. 'I', the number of iterations can be changed by instruction 3 with a proportional change in calculation time. Note that the program runs for 3.5 minutes when I = 6. New values of D/60, 90-B, and T/360 may be keyed in by instructions 4, 5 and 6 respectively if required. The default value of D/60 is for a target at the center of the nominal SAR swath, i.e. D = 166.30669 nautical miles or 308 km. Other useful values of D/60 for a target at the near and far edges of the swath are 2.32181 (258 km) and 3.22174 (358 km). Orbit inclination (180-B) and period T are the prelaunch parameters from Table 1.

Great circle navigation formulae do not permit start and stop coordinates to fall on the same meridian which means that the program fails for targets at the latitide extremes. The program was also not tested for targets in the Southern Hemisphere. Table VI gives the outputs from the calculator program for a target in Halifax, N.S. for both the ascending and descending modes. The program constants listed in Table V were used.

4.0 APPLICATIONS

The following two problems illustrate the application of the calculator program to SEASAT-SAR, point-target imaging.

4.1 Problem 1 Revolution Number to Image a Target

Given the table of nodes and the coordinates of the Citadel at Halifax, N.S., find the revolution numbers of the satellite orbits in the month of August 1978 during which SAR imagery of the target in the ascending mode can be collected.

The geographic coordinates of the Citadel are 44° 39' N, 63° 35' W and the corresponding geocentric latitude L_1, given by equation (20), is 44° 27' 24" N. Using these coordinates with the D/60 values for near and far range edges of the SAR swath, we find that the node ranges from 313.2775°

to 314.6705° E. Long. A search of the node table for the month of August, 1978, reveals four Rev. Nos. with ascending nodes in this range: 650 (Aug. 11); 851 (Aug. 25); 894 (Aug. 28); and 937 (Aug. 31).

4.2 Problem 2 SAR Image Time and Look Angle

Given a SEASAT SAR 'turn-on' during the ascending leg of Rev. No. 1238, when will the Citadel in Halifax, N.S. be imaged, and from what direction?

The node table predicts that Rev. No. 1238 on Sept. 21, 1978 will cross the equator at 314.5992° E. Long and at 13:33:31 G.M.T. The solution to problem 1 indicates that the target will be close to the near range edge of the SAR swath. Linear interpolation between the node limits gives a D/60 of 2.3674° with E_{cross} = 314.5996° and further refinement by trial and error yields a D/60 of 2.36765° with E_{cross} = 314.5992°. The trial and error process is faster if the target coordinates are left in memory and the number of iterations is reduced to one for each trial value of D/60. The distance of the Citadel from the near range edge of the swath is 5.0933 km. When the T_{lapse} of 12.9724 minutes is added to the published node time of 13:33:31, the image time becomes 13:46:29 GMT. Azimuth position of the satellite from the target at image time is H = 246.8755 degrees. The elevation to the satellite is given to adequate precision by the relation $\tan^{-1}$ (altitude/1.852D) - D/60. In this example it is 69.4281°.

5.0 TESTING THE PROGRAM

Detailed records were kept of the SEASAT operating parameters and are available to test the SEASAT Equator Crossing program. The satellite orbit was tracked from the ground and on-board sensors measured attitude and altitude for telemetry to recieving stations. This data was processed and assembled on one definitive attitude-orbit (A/O) tape for each 24 hour period of observation. Pitch, roll and yaw were listed at 5 second intervals on the attitude part of the tape. Position and velocity of the satellite in the geocentric inertial coordinate system were given in the orbit part of the tape at one minute intervals.

The test procedure will be to extract the appropriate data from the A/O tape and compare it with predictions made by the SEASAT Equator Crossing program. The common target for these tests will be the Halifax Citadel, which was imaged on September 21, 1978 during Rev. No. 1238 (A/O tape for day 264).

Synthetic aperture radar is distinguished by having three 'image' times. These are (i) the data acquisition time, when the target is in the center of the radar beam; (ii) the annotation time, which would be printed on the radar image if the data acquisition time were carried through a time-transparent correlation; and (iii) the side-looking time, which is the data acquisition time if the radar is properly aligned (90° clock), and also the annotation time when the radar is misaligned, after correction for earth rotation. The extraction of these 'image' times, and the node time, from the A/O tape will be described.

The model for the calculator program assumed that the SEASAT SAR operated only in the side-looking mode. It will be shown that a set of constants for the calculator program can be found to describe the satellite geometry in this imaging mode. Finally, the errors produced in the program output by using estimated program constants (from, for example, the prelaunch SEASAT orbit predictions) will be assessed.

5.1 Node Time

The satellite position and velocity were listed in the A/O tape at one minute intervals for an inertial, geocentric, Cartesian coordinate system. Z is along the earth's rotation axis (north positive). X is positive towards the Vernal Equinox, and Y completes the right hand system. The node time, 13:33:30.55 GMT for the ascending node of Rev. No. 1238, was extracted with an accuracy better than 0.33 second by linear interpolation to Z = 0. This value is in good agreement with the node time 13:33:31 GMT given by JPL in a recent SEASAT node table.

Coordinates X and Y at the node time (Z = 0) were also found by linear interpolation to better than 0.002° and converted to the equator crossing α in degrees east longitude (positive) relative to X = 0. The value of α for the ascending node of Rev. No. 1238 is 158.04999° E. Long. Conversion from the inertial coordinate system to one tied to the rotating earth was accomplished in two stages. First, the prime meridian at the beginning of day 264 was located from the orbit tape header as the Greenwhich hour angle γ = 359.51594°. Next, the earth rotation β between the beginning of day 264 and the node time was calculated to be 203.93411° using an earth rotation rate of 360.985647 degrees per day. The Greenwich hour angle and the apparent rotation of the satellite orbit plane are positive westward. Therefore the node becomes $|\alpha-\beta-\gamma|$ Mod 360 or 314.5999° E. Long. This is in acceptable agreement with a recent node table value of 314.5992° E. Long.

5.2 Data Acquisition Time

The following iterative procedure was used to extract the appropriate data from the A/O tape.

1. Select a trial data acquisition time T_a.
2. Interpolate the geocentric inertial coordinates of the satellite nadir at T_a and transform the longitude as was done for the node, but express it in degrees west.

3. Locate the intersection of the orbit plane with the equator at time T_a. (Start with the node; add earth rotation and subtract orbit precession during T_{lapse}; convert to degrees west).
4. Interpolate the pitch and yaw of the satellite at T_a and calculate the equivalent yaw.

5. Calculate the clock angle and compare with the equivalent yaw plus 90°. Repeat with new T_a until these angles are equal.

Orbit perturbations are included in the A/O tape data. To find the inclination of the unperturbed orbit plane for clock and heading calculations, precession was subtracted in the same way that it had been added in the description of the model in Section 2. Note, however that precession is due mainly to the earth's equatorial bulge and that it may not be valid to assume a constant rate.

The geocentric coordinates of the target, satellite nadir at T_a, and orbit plane/equator intersection are the three vertices of a spherical triangle which were labelled 3, 2 and 1 respectively in the equivalent right spherical triangle of Figure 2. Headings from 2 to 3 and from 2 to 1 (plus 180°) by the great circle navigation equations define the clock angle. These equations were also used to calculate the orbit inclination (heading 1 to 2), the distance and heading to target (2 to 3), and the angular distance between 1 and 2 which, with T_{lapse}, defines the effective orbit period. Swath heading and SEASAT heading were calculated by equations (16) and (19).

The SEASAT parameters which were calculated by this procedure are listed in data set 1 in Table VII and the SEASAT nadir coordinates at T_a are plotted as point 1 in the Standard Mercator projection of Figure 3. Both image time and T_{lapse} are shown in Table VII, although each can be derived from the other, given the node time. All angles are given in decimal degrees for ready comparison and easy plotting.

5.3 Side-Looking Time

The procedure used here was similar to that used to obtain the data acquisition time. The only difference was the value of the clock angle, which was 90°. The results are recorded as data set 3 in Table VIII and plotted as point 3 in Figure 3.

Constants for insertion into the SEASAT Equator Crossing program were derived from data set 3 in Table VIII. They are:

D/60 = 2.386264537 STO 6 ,
90-B =18.02810660 STO 7 ,
T/360= 0.279691542 STO 8 .

TABLE VII

SEASAT SAR IMAGING PARAMETERS

Parameter	1 A/O Tape (acquisition time)	2 A/O Tape (annotation time→MDA)
Latitude L_1 N	44.4566	44.4566
Longitude λ_1 W	63.5833	63.5833
E_{cross}/Node E	314.5999	314.5999
Node Time (GMT)	13:33:30.55	13:33:30.55
Latitude L_2 N	43.5326	43.3900
Longitude λ_2 W	66.6471	66.5435
'Image' Time (GMT)	13:46:29.43	13:46:26.78
T_{lapse} (min)	12.9813	12.9372
Clock Angle	91.4648	87.6052
Swath Heading	334.2966	334.2784
SEASAT Heading	332.1682	332.2248
Distance to Target (Km)	265.5531	264.8808
Heading to Target	66.1947	62.3992
Orbit/Equator Intersect W	48.6358	48.6249
Orbit Inclination	108.0281	108.0279
Orbit Period (min)	100.6888	100.6888

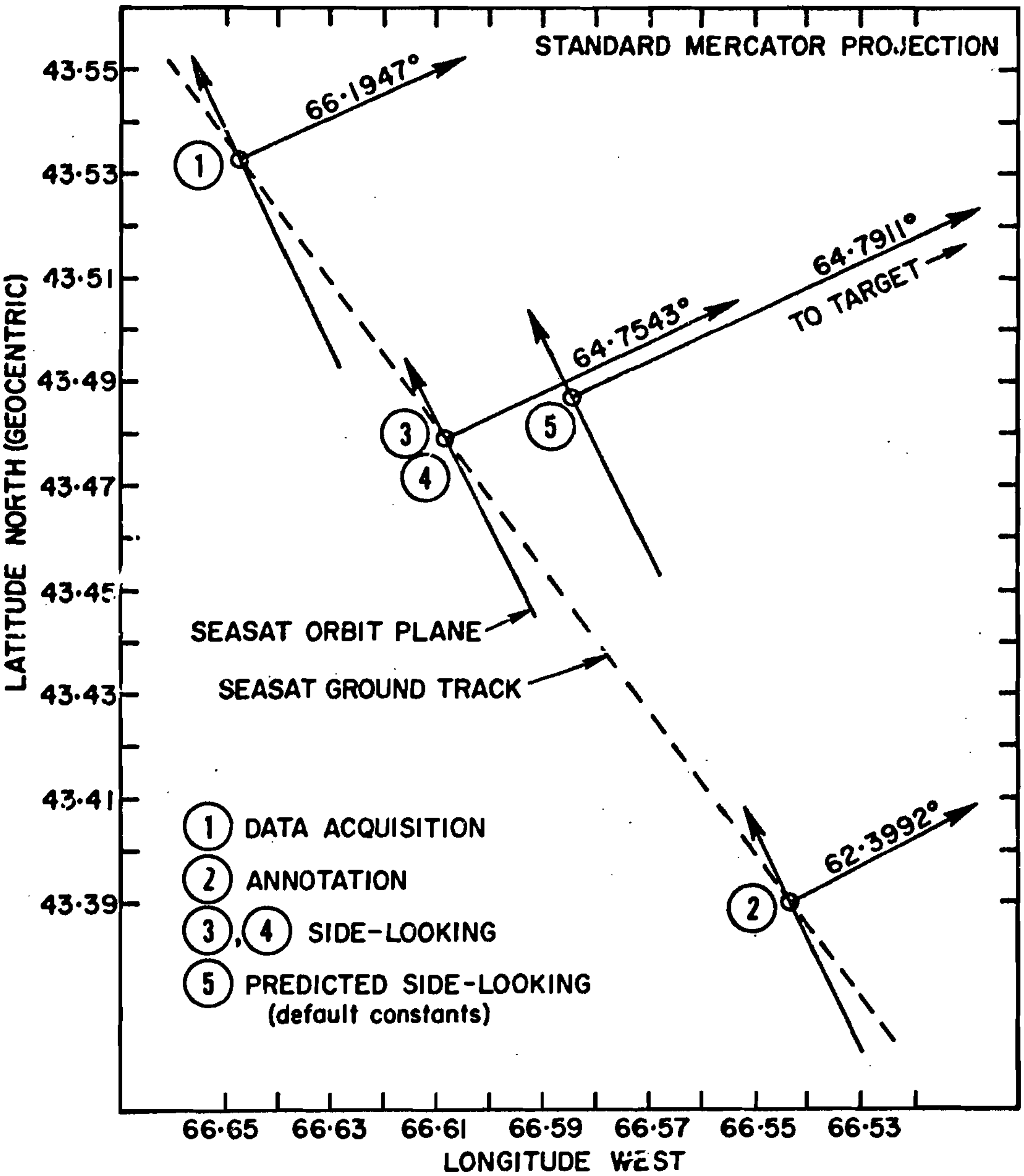

FIGURE 3 - SEASAT POSITIONS

These results are displayed as data set 4 in Table VIII. The exact agreement between data sets 3 and 4 demonstrates that the program is working properly. That is, a set of three constants can be found which will allow the program to fit data falling within the constraints of the SEASAT SAR model.

Consider now the predictions of the SEASAT parameters by the calculator program when only the prelaunch orbit period and inclination are available. The procedure, the same one used to solve Problem 2 in Section 4, is to adjust D/60 by successive approximation until E_{cross} and node are equal. The A/O tape node and node time are used here for comparison with the other data sets. However, the node tables were consulted for planning. The results are given in data set 5 of Table IX and plotted as point 5 in Figure 3. Differences between the SEASAT parameters from the A/O tape and those predicted by the SEASAT Equator Crossing program with default constants are also shown.

The increase in T_{lapse} is directly attributable to the increase in the orbit period from data set 4 to data set 5. Further, the decrease in the inclination angle accounts for the shifts in satellite longitude and in the distance between target and satellite nadir.

5.4 Annotation Time

Cross range position in a synthetic aperture radar image is determined by the Doppler frequency between radar and target. The displacement ΔX of the radar image in the cross range direction due to a target velocity v in the slant range direction has been shown by Raney [3] to be

$$\Delta X = Rv/V \tag{21}$$

where R is the slant range between radar and target and V is the velocity of the satellite track at the earth's surface. The direction of image displacement is such that a target velocity component towards the radar displaces the target image parallel to the swath heading.

Two phenomena generate non-zero slant range velocities of the earth's surface. These are the earth rotation (combined with orbit precession which in this case cancels part of the effect of earth rotation) and mis-aiming of the radar beam or squint. Earth rotation will be considered first.

The radar beam of the SEASAT SAR, in plan view, was nominally perpendicular to the orbit plane rather than to the satellite ground track. As a result, earth rotation contributed a ground velocity component in the slant range direction except at the extreme north and south limits of the orbit. Image displacement from this source is in cross range to the south. For the Halifax Citadel in Rev. No. 1238, the magnitude of the slant range velocity was estimated to be 0.1056 km per sec. This value includes orbit precession as well as earth rotation but ignores refinements in geometry that were not considered in the SEASAT SAR model described in Section 2. The corresponding image shift ΔX according to equation (21) is 13.3892 km and the

TABLE VIII

SEASAT SAR IMAGING PARAMETERS

Parameter	3 A/O Tape (side-looking time)	4 HP-67 (constants from 3)
Latitude L_1 N	44.4566	44.4566
Longitude λ_1 W	63.5833	63.5833
E_{cross}/Node E	314.5999	314.5999
Node Time (GMT)	13:33:30.55	13:33:30.55
Latitude L_2 N	43.4784	43.4784
Longitude λ_2 W	66.6077	66.6077
'Image' Time (GMT)	13:46:28.42	13:46:28.42
T_{lapse} (min)	12.9645	12.9645
Clock Angle	90.0000	90.0000
Swath Heading	334.2897	334.2897
SEASAT Heading	332.1897	332.1897
Distance to Target (Km)	265.1617	265.1617
Heading to Target	64.7543	64.7543
Orbit/Equator Intersect W	48.6317	48. 6317
Orbit Inclination	108.0281	108.0281
Orbit Period (min)	100.6889	100.6889

TABLE IX

SEASAT SAR IMAGING PARAMETERS

Parameter	3 A/O Tape (side-looking time)	5 HP-67 (default constants)	Diff.
Latitude L_1 N	44.4566	44.4566	-
Longitude λ_1 W	63.5833	63.5833	-
E_{cross}/Node E	314.5999	314.5999	-
Node Time (GMT)	13:33:30.55	13:33:30.55	-
Latitude L_2 N	43.4784	43.4873	+0.0089
Longitude λ_2 W	66.6077	66.5844	-0.0233
'Image' Time (GMT)	13:46:28.42	13:46:28.90	+0.48 sec
T_{lapse} (min)	12.9645	12.9725	+0.0080 min
Clock Angle	90.0000	90.0000	-
Swath Heading	334.2897	334.3085	+0.0188
SEASAT Heading	332.1897	332.2245	+0.0348
Distance to Target (Km)	265.1617	263.0470	-2.1147
Heading to Target	64.7543	64.7911	+0.0368
Orbit/Equator Intersect W	48.6317	48.6337	+0.0020
Orbit Inclination	108.0281	108.0000	-0.0281
Orbit Period (min)	100.6889	100.7500	+0.0611

change in image time is 1.9833 seconds.

The effect of satellite attitude on annotation time can be shown by expressing the pitch and yaw angles (-0.3587° and 0.3818° respectively at data acquisition time) as a squint angle in the slant range plane. Pitch and yaw normally deviate from the design specifications by less than 0.5°. Small angle approximation is therefore acceptable. Let the SEASAT SAR beam shift ϕs radians from the side-looking position in the slant range plane. The velocity component in the slant range direction due to ϕs is $v_s = \phi s V$ and the corresponding shift of the image in the cross range direction is, from equation (21) $\Delta X = \phi s R$. The change in time is $\Delta T = \phi s R/V$. Note that the image shift ΔX is equal in magnitude but opposite in direction to the extra distance the satellite travels beyond the side-looking position to acquire the radar data in the squint mode. In other words, the annotation time on the image will always be the side-looking time, to the small angle approximation, independent of the radar squint angle if corrections for earth rotation and precession have been applied.

The image shift ΔX from a squint angle of 0.008030 radians at the data acquisition position is 6.8099 km. The annotation time due to misalignment alone would be 1.0284 seconds earlier. These values are in good agreement with the great circle distance between the satellite nadir positions in data sets 1 and 3 of 6.8120 km, and the time difference of 1.0053 seconds between the data acquisition time and the side-looking time.

The annotation time in the Halifax frame from Rev. No. 1238 correlated by MDA (MacDonald Dettwiler and Associates) is about 2.66 seconds earlier than the acquisition time [4]. Interpolation from the Halifax frame yields an annotation time for the Halifax Citadel of 13:46:26.78 and the data acquisition time, 2.66 seconds later, of 13:46:29.44 GMT. This value of the data acquisition time is in good agreement with that in data set 1, 13:36:29.43, calculated from the A/O tape. However the annotation time is 0.33 seconds later than would be expected from the sum of the time diplacements from radar squint and earth rotation, 2.99 seconds. The reason for this difference is not known but is assumed to result from the approximations used in calculating the slant range velocity. The MDA annotation time was used to extract data set 2 in Table VII from the A/O tape and the coordinates for point 2 in Figure 3.

5.5 Discussion

The SEASAT ground track shown by the dotted line in Figure 3 represents the attitude - orbit tape data to within 0.002°, the error ascribed to the linear interpolation between orbit entries. Satellite positions along the ground track are less accurate and the data acquisition and side-looking positions, 1 and 3 respectively, depend on the unknown accuracy of the precession correction.

The attitude of the satellite is apparently not predictable and no attempt was made to incorporate an equivalent yaw correction into the calculator program.

Nominal beamwidth of the SEASAT SAR was 1.25° and the equivalent yaw at image time was about 1.4648°. Therefore, it is clear that the target could not have been illuminated from the side-looking or annotation positions at 2 and 3.

6.0 CONCLUSIONS

1. A program for the HP-67 programmable pocket calculator to extrapolate the SEASAT ground track up to one quarter of a revolution beyond the node has been developed and tested. It was shown that SEASAT orbit parameters which were measured during the satellite's lifetime can be fitted by the program using three constants.

2. Using the prelaunch design parameters as the default constants, the calculator program predicts SEASAT SAR imaging parameters which fall well within the limits imposed by the normal, but unpredictable, attitude variations. These limits introduce an uncertainty of a few seconds in the data acquisition time and up to a tenth of a degree uncertaintly in the satellite position coordinates. When accurate data acquisition times are required, the program can provide information to help aim a radar detector at the passing satellite.

7.0 REFERENCES

1. Helton, M.R. and Baerg, H.R., Seatrack Calcualtor Operating Instructions, JPL Document 622-52, 1978.

2. Deutsh, R., Orbital Dynamics of Space Vehicles, Prentice-Hall, Inc. 1963.

3. Raney, R.K., Synthetic Aperture Imaging Radar and Moving Targets, IEEE, Vol. AES-7, No. 3, P. 499, 1971.

4. Fielden, R.L., MacDonald, Dettwiler and Associates, Private Communication , April 15, 1980.

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A programmable pocket calculator is used to extrapolate the SEASAT orbit from the equator crossing to the position at which the synthetic aperture radar images a given target. The program predicts the coordinates of the satellite at image time, the Azimuth direction of the image at the target, and the time elapsed between equator crossing and imaging. Program predictions are compared with measured SEASAT data from the definitive attitude-orbit files.

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