TABLE DRIVEN σ^O RETRIEVAL FOR A PENCIL BEAM SCATTEROMETER

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Abstract—NASA has designed a new pencil-beam scatterometer, *Seawinds*, which is scheduled to be launched on two missions before 2001. The ground data processing to determine the normalized radar backscatter (σ^o) from *Seawinds* measurements is too computationally intensive to be performed in real time. Therefore, it is necessary to pre-calculate and tabularize some of the calculations. A tabulation method has been developed which will assist in calculating σ^o and in locating the slice centers for the *Seawinds* measurements. The table driven part of the calculation is expected to be accurate to within 0.1 dB for σ^o and 160 meters for the slice centers.

Introduction

NASA has designed a new pencil beam scatterometer called *Seawinds*. *Seawinds* is scheduled for two missions. *Seawinds* will be launched on its first mission, *Seawinds on QuikSCAT*, in May of 1999 as a replacement for the *NASA Scatterometer* (NSCAT). *Seawinds* is also scheduled to operate aboard the the Japanese satellite *ADEOS II* which is scheduled for launch in November of 2000.

Measurements made by *Seawinds* will be used to determine the speed and direction of the wind over the ocean. The measurements will also be used to produce images of the rain-forests, the polar ice caps, and other areas of the Earth. These images can be used to analyze large scale changes in the Earth's environment.

Seawinds will measure the normalized radar backscatter (σ^o) over the ocean and land. The antenna uses the following two beams:

- The inner beam is horizontally polarized with a boresight at approximately 40° elevation.

- The outer beam is vertically polarized with a boresight at approximately 46° elevation.

Each antenna beam will illuminate an elliptical area on the Earth called an "egg."

Seawinds uses a chirped signal and a digital processor to divide this egg into 12 "slices." The digital processor has 8 different operational modes which adjust the width of the slices. Figure 1 shows the 3 dB contours of the egg and the slices for mode 6 which is the nominal mode. The slice widths are defined by baseband frequencies. Zero baseband frequency will be at the boresight of the

antenna if the satellite has no perturbations and there are no errors in the Range/Doppler tracking tables. The digital processor uses an FFT to separate the power returned from the different slices. The power returned from the slice (P_r) and the value of σ^o over the slice are related through the "X-factor":

$$\sigma^o = \frac{P_r}{X}. \tag{1}$$

The X-factor is a function of the position of the satellite, the pointing direction of the antenna, the antenna gain, and other factors. The X-factor is derived from the integral form of the radar equation [10]. Because the numerical integration required to calculate X is so time consuming, this calculation cannot be performed as fast as *Seawinds* takes measurements. *Seawinds* measurements are collected on 5 ms intervals.

All of the parameters required to calculate X can be known, or at least closely approximated before hand. This means it is possible to pre-calculate X and enter it in a lookup table. The lookup table must also provide a way to compensate for slight changes in the parameters used to calculate X.

This report discusses the method used to tabularize X. It includes the description of how the method was developed, and an assessment of its expected accuracy.
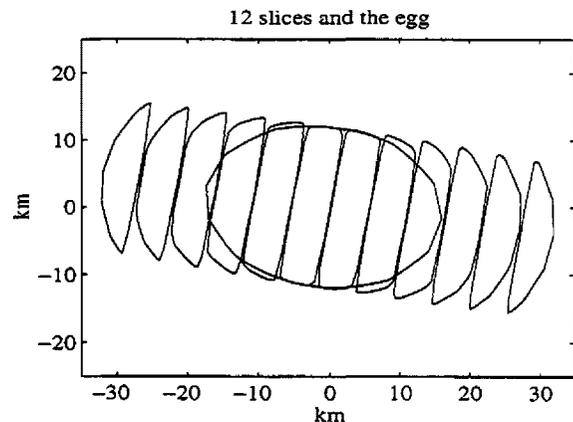

Figure 1: The 3 dB contours of the egg and 12 slices for *Seawinds* plotted on a kilometer grid.

Calculating X

X can be defined as the product of two factors [9]:

$$X = X_{cal}X_{int}.$$

X_{cal} is a calibration constant that will be included by the ground system. X_{int} is obtained through numerical integration using the antenna gain pattern as well as spacecraft and antenna position relative to the Earth. This paper discusses the calculation of X_{int} which for notational convenience will simply be referred to a X throughout the rest of this paper . The equation to find X for a slice is

$$X_{slice} = \frac{1}{NN_{p,t}} \sum_{i \in F} \delta A_i \cdot R_i \cdot P_{slice}(f_{b,i}). \quad (2)$$

N is the number of points in the processor FFT, 1024. The number of samples of the transmitted pulse captured by the range gate is $N_{p,t}$, which is usually 708. F is the area on the Earth's surface that is illuminated by the antenna beam. The size of each incremental area on the ground is δA_i. R_i is the response of each incremental area defined by

$$R_i = \frac{g_i(t_{trs})g_i(t_{rec})}{r_i^4} \quad (3)$$

where $g_i(t_{trs})$ and $g_i(t_{rec})$ are the gain over A_i at the transmit time and receive time, respectively. The variable r_i is the slant range to A_i. $P_{slice}(f_{b,i})$ is the processor response for that slice at $f_{b,i}$, the baseband frequency of A_i. P_{slice} is a sum of sinc functions that can be closely approximated with a rect function that has a response of 1 for frequencies inside the slice, and a response of 0 for frequencies outside of the slice.
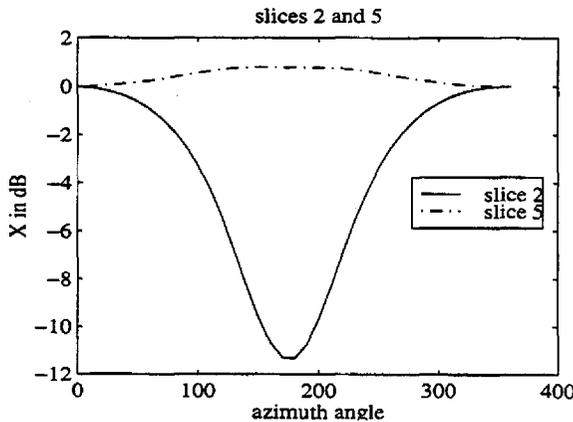
The egg is simply the sum of the inner 10 slices. This means X for the egg is simply the sum of the X values for the inner 10 slices.

Dr. David Long, professor of Electrical Engineering at BYU, and a team of BYU students, myself included, have written a program that calculates X. In developing the program, we kept in close correspondence with the Jet Propulsion Laboratory (JPL) and even included some of JPL's geometry routines. We have used this program to analyze the behavior of X and find a way to make a table of X values.

Tabularizing X

The value of X changes depending upon the orbit time (T) and azimuth angle (ϕ) of *Seawinds*. I conducted studies to determine the range of the variation in X and to find possible ways to parameterize X as a function of T and ϕ. For all of these studies, X was converted to dB. For the rest of this report references to X are given in dB.

The value of X changes significantly for different values of ϕ. Figure 2 shows the relationship between azimuth angle and X for slices 2 and 5 for a constant T. For slice 2, X varies by over 15 dB. The acceptable error in X is less than 0.1 dB, so it is obvious that there needs to be a way to parameterize X as a function of ϕ. Fig. 2 shows that even the variation in X for slice 5 is more than 0.5 dB. In a previous study, it was shown that slices 5 and 8 have the smallest variation with ϕ [2].

The orbit time[1] of the spacecraft also has an impact on X. Figure 3 shows how X varies with orbit time for

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[1]The orbit time is defined as the time in seconds that has elapsed since the spacecraft ascended past the equator. The full orbit of the spacecraft is approximately 6060 seconds.
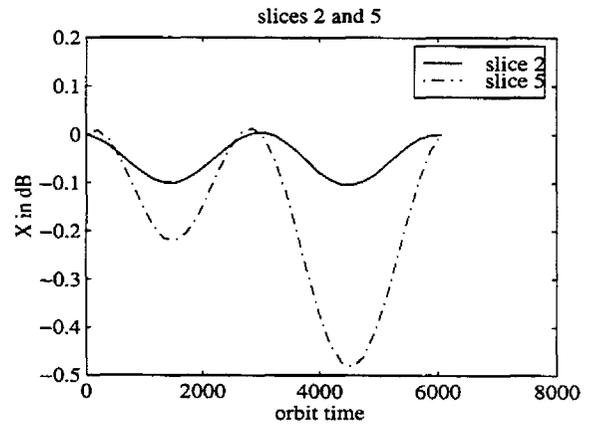

Figure 2: Variation of X with azimuth angle for slices 2 and 5. X has been normalized for easier comparison.

Figure 3: X varies with orbit time for slices 2 and 5. X has been normalized for easier comparison.
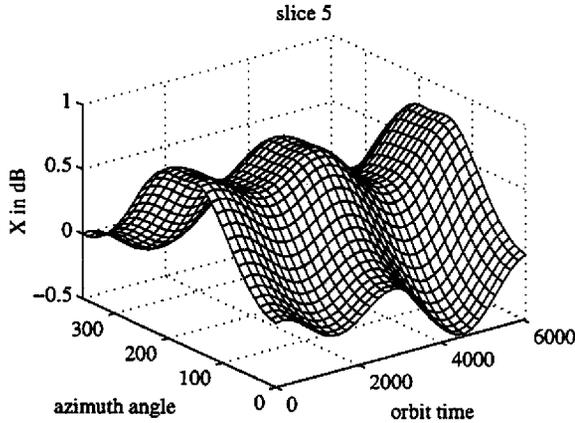
slice 5

Figure 4: X variations over the entire orbit time and azimuth range for slice 5. X has been normalized.

parameter	QuikSCAT	ADEOS II
roll	0.1	0.3
pitch	0.1	0.3
yaw	0.1	0.3
eccentricity	2×10^{-4}	3×10^{-5}
arg. of per.	$10°$	$2°$
semi-major axis	≈ 0	1 km

Table 1: The 3σ (3 times the standard deviation) values of the spacecraft perturbations expected for *QuikSCAT* and *ADEOS II*.

slice 2 and slice 5 with ϕ held constant. The variation is less than 0.5 dB for each slice. This is smaller than the variation in X over the range of ϕ, but it is still large enough that it needs to be accounted for.

Figure 4 shows a three dimensional graph of how X varies over the entire azimuth and orbit time range. It appears that effects of azimuth and orbit time are fairly independent of each other.

Numerous methods of parameterizing X as a function of azimuth angle and orbit time have been investigated. Some of the methods that have been analyzed are

- a combination of a polynomial fits for T and ϕ,

- a combination of trigonometric functions of T and ϕ,

- a table containing X at discrete values of T and ϕ to be interpolated using bicubic interpolation, and

- a table containing X at discrete values of T and ϕ to be interpolated using bilinear interpolation.

The method that was finally chosen is to use a table containing X for discrete values of T and ϕ that will be interpolated using bilinear interpolation. This method was chosen mainly because it is simple. Research showed that if the table included X values for 15 values of T and 18 values of ϕ then the interpolation error would be less than 0.1 dB [3]. The final table includes 32 values of T and 36 values of ϕ, so the interpolation error should be significantly less than 0.1 dB. In my analysis of the final table accuracy, I showed that the majority of the error in X comes from the perturbation correction algorithm, and not from the interpolation of the X-table [4]. The perturbation correction algorithm is discussed in the next section.

Including Perturbations

The major challenge in creating an X-table is finding a way to correct for possible spacecraft perturbations and errors in the Range/Doppler tracking tables. The algorithm that was finally developed is quite accurate and simple considering the magnitude of the problem.

There are two types of perturbations:

1. attitude perturbations and

2. orbit perturbations.

The attitude perturbations include changes in the roll, pitch, and yaw of the spacecraft. The orbit perturbations include changes in eccentricity, the argument of perigee, and the semi-major axis. The expected perturbations for *QuikSCAT* and *ADEOS II* are given in Table 1.

These perturbations cause a large enough change in X for the slices that it is necessary to use some correction method. Two methods were proposed to correct X. The first method is termed the "K-factor" approach. The K-factor adjusts X depending on the response (R_i in Eq. 3) at the center of the slice. Analysis showed this method to be accurate and robust. However, one potential difficulty of this method is that it requires the ground system and the K generation software to calculate the exact same values for the gain and range of the slice centers [9].

The other correction method uses the baseband frequency at the boresight of the antenna beam (Δf) to correct X. This method uses the table of X values discussed in the *Tabularizing X* section. The value in this table is referred to as the nominal value of X, or X_{nom}. The value of X corrected for perturbations is $X_{pert} = X_{nom} + \Delta X$ where ΔX is a function of the different perturbations. Originally it was thought that ΔX would include each perturbation separately. It was later discovered that the effect of all of the perturbations could be combined by using Δf. Figure 5 shows a plot of X for 50 different combinations of attitude and orbit perturbations versus the Δf. A third degree polynomial can be

used to approximate ΔX as a function of Δf. i.e.

$$\Delta X = A + B \cdot \Delta f + C \cdot \Delta f^2 + D \cdot \Delta f^3. \quad (4)$$

This is the method used in the final version of the X-table. The overall accuracy of X_{pert} is discussed in the section entitled *Accuracy of the X-table*.

Effects of Topography

The elevation of the local topography will also alter the value of X. An increase in the height of the surface is similar to a decrease in the altitude of the spacecraft. Therefore, using the Δf correction scheme which is used to correct X_{nom} for orbit perturbations will work for the topography elevation as well [5]. The relationship between topography elevation and Δf is linear as shown in Fig. 6. A new Δf_{total} can be defined as

$$\Delta f_{total} = \Delta f + S \cdot h_{topo} \quad (5)$$

where h_{topo} is the elevation of the local topography and S is the slope of the linear fit of Δf as a function of h_{topo}. Δf_{total} can be used in the place of Δf for the calculation of X_{pert}.

Range Gate Clipping

The effects of range gate clipping have been analyzed to determine if X needs to be corrected for this factor as well. Range gate clipping occurs when a portion of the signal returned from a slice is cut off by the range gate. Research found that range gate clipping is expected to cause X to vary by less than 0.1 dB for the inner 10 slices. The analysis included all 8 resolution modes and both beams. The analysis also showed that X is expected
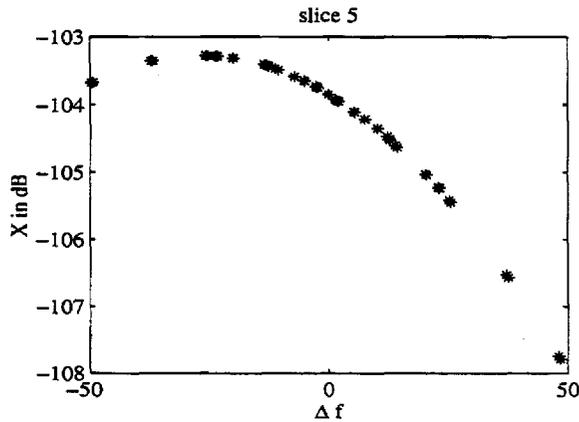
to vary by less than 0.02 dB for the inner eight slices for resolution modes 2 through 8, both beams. These variations are small enough that they can be ignored for the most part. However, a G-factor is included in the table in case it is later decided that the effects of range gate clipping need to be included. The equation to obtain X using the G-factor is

$$X = X_{nom} + 10\log_{10}(G) \quad (6)$$

where, as mentioned earlier, X is in dB.

Tabularizing Slice Center Locations

The question arose as to whether there is a way to tabularize the slice centers. This would simplify ground data processing. The idea of tabularizing the latitude and longitude of the slice centers was investigated, but dismissed as being too complicated. Still, desiring to find some way to parameterize the slice centers, the idea of tabularizing the elevation (θ) and azimuth (ϕ) angles[2] of the slice centers was investigated [1]. It was discovered that these values could be made into a table with the same resolution as the X_{nom} table and still have acceptable interpolation errors. The elevation and azimuth angles of the slices were also found to be linear functions of Δf for the different sets of perturbations.

The X-Table

This section describes how the X-table is used. For each pulse that *Seawinds* transmits and receives, the table is

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[2]These angles are in the spacecraft coordinate system. For the spacecraft coordinate system, the azimuth angle is the angle in the plane parallel to the surface of the Earth referenced from the velocity vector of the satellite. The elevation angle is referenced from nadir, or directly below the spacecraft.
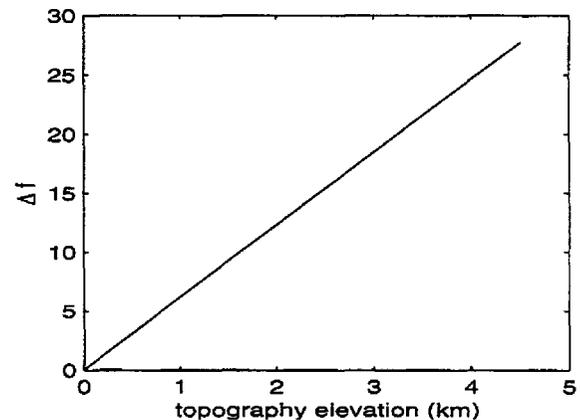

Figure 5: Variations in X for slice 5 using 50 different combinations of expected perturbations. X is plotted as a function of the baseband frequency at the boresight.

Figure 6: Δf is a linear function of h_{topo} (the elevation of the local topography).

used to calculate X for all of the slices and the egg. The X values retrieved from the table are in dB. The X-table is also used to calculate the slice centers.

The first step in using the table is obtaining the baseband frequency at the boresight of the antenna. The necessary computations are made to find Δf using the radius of the Earth at sea-level. Then, S is retrieved from the table and Δf_{tot} is calculated using Eq. 5 with the local topography elevation.

The second step is using the table is to find the value of X using

$$X = X_{nom} + A + B\Delta f_{tot} + C\Delta f_{tot}^2 + D\Delta f_{tot}^3 \quad (7)$$

where X_{nom}, A, B, C, and D have been retrieved from the table and are specific to the slice for which X is being calculated. This must be done for each slice and the egg.

The slice centers can also be calculated using the X-table. The equations to obtain the azimuth and elevation angles of the center of each slice are

$$\phi = \phi_o + A_\phi + B_\phi\Delta f_{tot}, \text{ and}$$
$$\theta = \theta_o + A_\theta + B_\theta\Delta f_{tot}. \quad (8)$$

A_ϕ, B_ϕ, A_θ, and B_θ are all retrieved from the table. θ_o and ϕ_o are the elevation and azimuth angles, respectively, of the boresight for that beam. These angles are in the spacecraft coordinate system. When the conversion from elevation and azimuth to latitude and longitude is made, the elevation of the local topography is included in the radius of the Earth. The X-table is discussed in more detail in the technical report *How to Produce and Use the X-factor Table* [6].

Accuracy of the X-Table

Brian Jones conducted studies to determine the expected accuracy of the X-table for both *QuikSCAT* and *ADEOS II* [8, 7]. The analysis was performed using mode 6 which is the nominal resolution mode. It included both the inner and outer beam. The maximum standard deviations for the inner 8 slices are shown in Table 2. The overall result is that X should meet the requirement of

parameter	QuikSCAT	ADEOS II
X	.02	0.6
ϕ (meters)	75	110
θ (meters)	51	110

Table 2: The maximum standard deviations for the inner 8 slices for mode six, both beams included. The standard deviations in slice center azimuth (ϕ) and elevation (θ) angles have been converted to meters to make them easier to comprehend.

being accurate to within 0.1 dB for the inner 8 slices, and the slice centers should be accurate to within 160 meters.

Conclusion

The people involved in the X-factor project at BYU have worked closely with JPL to develop an accurate robust method for table driven σ^o retrieval for *Seawinds*. The X-factor and slice centers were calculated by BYU and JPL independently and then compared. Any differences between the two were resolved.

The table driven part of the ground data processing for *Seawinds* should be accurate to within 0.1 dB for σ^o and 160 meters for the slice centers. Many other variables will determine the final accuracy of the *Seawinds* data. There is no guarantee that the X-table is 100% bug free. Special care will still be taken after *Seawinds on QuikSCAT* is launched to ensure that the X-table is as accurate as the research thus far has shown it to be.

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