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First-Order Model for Space-Based Active-Array SAR

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FIRST-ORDER MODEL FOR SPACE-BASED ACTIVE-ARRAY SAR

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Defence Research Establishment Ottawa

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Abstract

The initial steps taken by a radar designer to evaluate new design concepts or to review designs from outside sources involve iterative use of first-order analysis algorithms to couple high-level functional descriptions of the radar to viable system specifications. These analyses provide the foundations for detailed design studies or for detailed performance predictions. This report and its companion Excel spreadsheet provide a first-order analysis package for the current generation of active-array space-based SAR systems. The analysis package covers aspects of orbit parameter selection, observation geometry, active array design, image properties and data handling and data link requirements. Analysis procedures that use multiple, systematic, model trials are discussed.

Résumé

Les étapes initiales suivies par un concepteur de radar pour évaluer les concepts des nouveaux modèles ou pour examiner des modèles provenant de sources extérieures sont basées sur l'utilisation itérative d'algorithmes d'analyse du premier ordre permettant de mettre en correspondance des descriptions fonctionnelles de haut niveau du radar et des spécifications de systèmes viables. Les analyses ainsi effectuées servent de fondement aux études de conception détaillées ou aux prévisions de performances détaillées. Le présent rapport et la feuille de calcul Excel qui l'accompagne fournissent un ensemble d'analyse du premier ordre pour la génération actuelle de systèmes RAS spatiaux à réseau actif. L'ensemble d'analyse englobe les aspects de la sélection de paramètres d'orbite, de la géométrie d'observation, de la conception d'antenne à réseau actif, des propriétés des images et des exigences relatives à la manipulation des données et aux liaisons de données. Le document traite de procédures d'analyse faisant appel à des essais multiples et systématiques de modèles.

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Executive summary

Background

Space-based Synthetic Aperture Radars (SARs) that are currently under development and the next generation of these instruments are and will be based on active-array antenna designs. In this class of instrument portions of the radar transmitter, radar receiver and radar beam control are distributed over the non-radiating surface of a deployable, phased-array antenna. The active-array architecture is robust for component failures, fails gracefully with age, and is less costly than previous, monolithic transmitter/receiver designs. Active-array radars are non-reciprocal instruments and have independent transmit and receive characteristics.

The first stage of evaluating a radar design proposal or a functional description of a foreign radar is to perform a first order analysis that generates sets of possible system parameters from the more general descriptive material provided. The results from this analysis, when combined with the assumptions used to generate them provide a reasonably detailed view of viable design alternatives, indications of design difficulties that are implicit in the desired performance, and an understanding of the probable performance of the instrument. This report documents spreadsheet analysis software developed for J2 STI analysts to provide a first-order evaluation of space-based active-array SAR systems.

Active-Array SAR Spreadsheet

The spreadsheet described in this report is a version of a radar designer's first-order model for space-based active-array SAR systems. It provides the user with a tool kit for the evaluation of a number of key design parameters and provides a reasonable overview of the properties of the instrument being investigated. The model is not exhaustive in that there are other parameters that can be added to both the input list and the derived parameter set. The derivation of error budgets and design margin budgets is not addressed. In the classical design process, which follows the sequence: functional specification→system specification→module specification→component specification→part specification, this model starts from functional parameters and yields much of the information needed to define system specifications. It is a first-order tool that can be used to define and investigate design options that arise from functional requirements.

To enhance the value of this report for analysts using the spreadsheet software, the report organization follows the spreadsheet architecture. Topics are introduced in order from the top of the spreadsheet. Variables are defined as they occur and are summarized in tabular form at the start of each section. The spreadsheet calculations are documented cell-by-cell following the order of the November 2001 spreadsheet version that corresponds to this report. Each cell is cross-referenced with its algorithm and explanation for ease of use. As a further aid, Annex B lists all variables and provides cross-references.

The Excel workbook containing the software has been written as two pages. The main page (Control sheet) contains all user inputs and is designed for printing as an analysis report on a single legal-size sheet. The second page (Constants and Utilities) performs background calculations and has no user inputs. It is not normally printed.

In soft-copy versions of the report, Annex A contains a link to the spreadsheet software that is contained on the same recording medium. The Active-Array SAR software can be opened for use by triggering the link.

Livingstone, C. E., 2002. A First-Order Model for Space-based Active Array SAR.
DREO TR 2002-018. Defence Research Establishment Ottawa.

Sommaire

Contexte

Les radars à antenne synthétique (RAS) spatiaux qu'on met actuellement au point sont basés sur des modèles d'antenne à réseau actif et ceux de la prochaine génération le seront également. Dans cette classe d'instruments, des éléments de la commande du faisceau radar, de l'émetteur radar et du récepteur radar sont répartis sur la surface non rayonnante d'une antenne réseau déployable à commande de phase. L'architecture de l'antenne à réseau actif est peu sujette aux défaillances des éléments, ses défaillances apparaissent progressivement avec l'âge et son coût est moins élevé que celui des modèles d'émetteurs/récepteurs monolithiques précédents. Les radars à antenne à réseau actif sont des instruments non réciproques et ils possèdent des caractéristiques d'émission et de réception indépendantes.

La première phase de l'évaluation d'une proposition de modèle de radar ou d'une description fonctionnelle d'un radar étranger consiste à effectuer une analyse du premier ordre qui génère des ensembles de paramètres possibles du système à partir du matériel descriptif plus général fourni. La combinaison des résultats de cette analyse et des hypothèses sur lesquelles ils sont fondés permet d'obtenir un aperçu assez détaillé de modèles de rechange viables, des indications des difficultés de conception qui sont inhérentes à la performance désirée, et des informations sur les performances probables de l'instrument. Le présent rapport décrit le logiciel tableur d'analyse élaboré à l'intention des analystes du J2 IST dans le but de permettre une évaluation du premier ordre des systèmes RAS spatiaux à réseau actif.

Feuille de calcul pour le RAS à réseau actif

La feuille de calcul décrite dans ce rapport est une version d'un modèle du premier ordre d'un concepteur de radar pour les systèmes RAS spatiaux à réseau actif. Elle fournit à l'utilisateur une boîte à outils pour l'évaluation d'un certain nombre de paramètres de conception clés et donne un aperçu raisonnable des propriétés de l'instrument à l'étude. Le modèle n'est pas exhaustif, puisque d'autres paramètres peuvent être ajoutés tant à la liste d'entrée qu'à l'ensemble de paramètres déduits. La détermination des bilans d'erreurs et des bilans de marge de conception n'est pas traitée. Dans le processus de conception classique, qui respecte la séquence suivante : spécification fonctionnelle→spécification de système→spécification de module→spécification d'élément→ spécification de pièce, ce modèle part des paramètres fonctionnels et fournit la plus grande partie de l'information requise pour définir les spécifications du système. Il constitue un outil du premier ordre qui peut être utilisé pour définir et examiner les options de conception qui découlent des exigences fonctionnelles.

Pour qu'il soit d'une plus grande utilité aux analystes se servant du logiciel tableur, le rapport a été structuré de façon à suivre l'architecture de la feuille de calcul. Les sujets sont présentés dans l'ordre à partir du haut de la feuille de calcul. Les variables sont définies à mesure qu'elles apparaissent et elles sont résumées sous forme de tableau au début de chaque section. Les calculs sont décrits cellule par cellule, en suivant l'ordre de la version de la feuille de calcul de novembre 2001 qui correspond au présent rapport. Pour chaque cellule, des

références croisées sont établies avec l'algorithme correspondant et les explications connexes, dans le but de faciliter l'utilisation. L'annexe B, qui contient la liste de toutes les variables et fournit des références croisées, constitue une aide additionnelle.

Le classeur Excel contenant le logiciel est un fichier de deux pages. La page principale (feuille de contrôle) contient toutes les données d'entrée de l'utilisateur et elle est destinée à être imprimée sous forme de rapport d'analyse sur une seule page grand format. La deuxième page (constantes et utilitaires) effectue des calculs d'arrière-plan et ne comprend pas de données d'entrée de l'utilisateur. Normalement, elle n'est pas imprimée.

Dans les versions électroniques du rapport, l'Annexe A comprend un lien vers le logiciel tableur contenu sur le même support d'enregistrement. Le logiciel relatif aux RAS à réseau actif peut être ouvert pour fins d'utilisation en cliquant sur le lien.

Livingstone, C. E.. 2002. First-Order Model for Space-Based, Active-Array SAR. DREO TR 2002-018 Centre de recherches pour la défense Ottawa.

Table of contents

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1. Introduction

The process of assessing partially known radar designs is very similar to the process of starting the design of a new radar system. In both cases a large number of system parameters need to be inferred from a small number of "known" or "desired" functional parameters and a number of "reasonable" guesses. In both cases a first-order model is used to validate the compatibility of the input parameter set, to explore possible alternatives and to identify possible trade-offs for further study. At the end of the first-order investigations, the refined parameter set that has evolved and the trade-off possibilities form the inputs to a more detailed sequence of design iterations. At the next level, not included in this tool error budgets are established to test the impact of design choices on aggregate parameters such as radiometric accuracy, phase noise, integrated sidelobe levels, etc.

The spreadsheet described in this note is a version of a radar designer's first-order model for space-based active-array SAR systems. It provides the user with a tool kit for the evaluation of a number of key design parameters and provides a reasonable overview of the properties of the instrument being investigated. The model is not exhaustive in that there are other parameters that can be added to both the input list and the derived parameter set. The derivation of error budgets and design margin budgets is not addressed.

To put the spreadsheet model into context, the design process follows the sequence: functional specification→system specification→module specification→component specification→part specification. This model starts from functional parameters and yields much of the information needed to define the system specification.

2. Model Assumptions And Description

The models used to infer radar properties from basic functional data are specification driven. The user inputs are treated as specifications that must be met or exceeded by the minimum radar design arising from the model calculations. As the input specifications have different levels of reliability, the models can be used to test the implications of varying those that are least firm.

2.1 Orbits

The model is specifically designed for orbiting SAR imaging systems. All orbits are assumed to be circular and are parameterized by the satellite altitude, the orbit inclination, and the ascending node (north-bound equator crossing) longitude. Orbit decay and precession are not included. Both retrograde (satellite longitude changes in the opposite direction to earth rotation) and prograde (satellite longitude changes in the direction of earth rotation) orbits are included. In geographic coordinates, the satellite position and direction of motion are defined in terms of the node (ascending = moving northwards, or descending = moving southward), satellite latitude, satellite longitude, track angle (the satellite direction measured clockwise from north) and the central angle of the orbit (the angle formed at the earth centre by the satellite position and ascending node).

2.2 Imaging Geometry

The earth is modeled as an ellipsoid of revolution (GEM6 model) that can be treated as locally spherical. Earth coordinates are defined in terms of latitude and longitude using the conventions:

- North Latitude is positive
- South Latitude is negative
- West longitude is positive
- East longitude is negative.

All relationships between the satellite, the radar imaging geometry, and the earth surface are modeled using spherical geometry. Earth rotation effects are included. For imaging geometry calculations, the radar is modeled in terms of its swath, its resolution, the slant range, incidence angle, earth centre angle (or stand-off distance on the earth surface from the satellite track), and the range over-sampling ratio. The satellite position is inferred from the incidence angle at a desired observation point that lies either to the right or to the left of the satellite track (the orbit is determined by the target). The local earth radius used throughout the model is defined by the latitude of the selected observation point. Radar swaths are modeled in both slant range and surface distance and are defined by input swath widths and by the incidence angle at the near edge of the swath. A coupling between the radar beam squint and the earth rotation is modeled as a means of minimizing the Doppler centroid of the radar.

Alternate implementations of the geometry model that fix the ascending node longitude and derive all relationships from the satellite position and the target range and incidence angle (the target is determined by the orbit) could be easily implemented but are not included in this version.

2.3 Radar Model

The radar system is modeled in two parts: the Antenna and the Radar. The models used extract first order radar properties from basic inputs. More refined radar descriptions can be derived from the model results but are not included here.

The Antenna component of the model uses high-level parameters to infer the radiation properties of the antenna (azimuth and elevation beamwidths, antenna gain and elevation steering range). Uniform weighting of the radiating surface is assumed. These, in combination with the minimum acceptable transmitter power are used to define the minimum row and azimuth sub-array architecture needed to meet electronic steering, minimum power, and fabrication symmetry constraints. When the variation of the illumination of a specified swath exceeds reasonable limits for an aperture-limited radar beam, a broadened (but otherwise unshaped) swath-limited beam is used to derive the antenna sub-array requirements. The minimum number of transmit-receive modules and the maximum range of electronic azimuth-steering angles are estimated.

The Radar component of the model uses a reference incidence angle for which the radar specifications set is deemed to be valid to estimate the minimum peak transmitter power under aperture limited and swath limited beam assumptions. The minimum of these is used in the Antenna model to estimate the number of transmit-receive modules and, thus, the peak transmitter power of the radar. The minimum pulse repetition frequency, the location of, and the relative received power from, the first range ambiguity, the duration of the required receiving window and conflicts between the receiving window and the transmitting period are also estimated in this part of the calculation.

The radar model also estimates the RF sampling rate, burst and average data rates, the recorder capacity (with and without data compression), downlink channel capacity and downlink time dilation. A small set of image data properties are estimated.

2.4 Spreadsheet Structure

The spreadsheet calculations are configured as a set of interacting modules on two work sheets. The ’Control sheet’ has user inputs and the ‘Const and Util’ (Constants and Utilities) worksheet contains only constants and program utilities. The worksheet entries are direct user inputs and control switch selections. The following sections of the report discuss each module in detail and link the active spreadsheet cells to the implemented equations and implicit assumptions made in their formulation.

3. Excel Software Implementation

The spreadsheet calculations use standard EXCEL functions. The definition ranges of inverse trigonometric functions and singularities in the geographic angle coordinates are compensated by the use of condition switches that take the forms:

- (1+X)/2, (1-X)/2 where X is a switch setting with value 1 or -1
- FLOOR(Y/Z,1), CEILING(Y/Z,1), where Y and/or Z are continuous angle variables, are chosen to have values of 0 or 1.

The “condition switches” are mainly used with an angle multiplier that defines the angle quadrant.

All EXCEL trigonometric functions have their arguments in radians. The spreadsheet reports angles in degrees. **Transformations between radians and degrees are not included in the equations in this manual.**

The form of the EXCEL IF statement is IF(a,b,c) where “a” is an expression, “b” is a function that is executed if “a” is true, and “c is a function that is executed if “a” is false.

3.1 Control Sheet “Platform” Module

The "Platform” module models basic properties of the satellite orbit and spacecraft attitude when provided with:

- satellite altitude,
- orbit inclination,
- a reference latitude at which the radar specifications are defined
- the settings of user activated switches.

A terrain height parameter is listed but is not currently used.

The calculations assume a circular orbit and consider two cases:

- the radar beam points broadside to the track
- the radar beam points to zero Doppler.

All calculations are based on a strip-mapping SAR. The case of an arbitrary fixed or dynamic radar beam squint is not addressed.

3.1.1 Inputs

The input variables used in this module, their symbols and units are listed in table 1.

Table 1 “Platform” module input parameters. Switches are dimensionless.

Parameter	**Type**	**Symbol**	**Unit**	**Cells**
Satellite altitude	User input	H	km	E10
Terrain height	User Input	h	m	E11
Orbit inclination	User Input	i	deg	E12
Reference incidence angle	User Input	ψ_R	deg	E13
Squint selector	Selector switch	S_S		C14,E14
Pass segment	Selector Switch	S_N		C16,E16
Satellite latitude	Increment Switch	S_ξ	deg	C18,E18
Hemisphere	Selector switch	S_H		C20,E20
Desired orbit repeat cycle	User Input	N_D	days	E21

The satellite altitude, orbit inclination and reference incidence angle entered in this module have significant impact on the entire spreadsheet model. The altitude and inclination entries define major geometrical features. The reference incidence angle couples other critical inputs (Eg., noise equivalent cross section) into the model at the functional definition geometry.

The selector switches are built with EXCEL “Combo Box” controls and use labels stored in the hidden C and L columns of the spreadsheet. The selection process generates a list “item number” in hidden column C that is translated into a switch parameter ±1 by algorithms of the form Exx=(3-2Cxx). The latitude increment switch is built with an EXCEL “Spinner” that successively increments a number between 0 and 40 in C18. The number is translated into a latitude in cell E18 by the algorithm: E18=(40-C18)*0.025*θ_{Max} (θ_{Max} is defined in Table 3.)
Variables imported into this module from other work sheets are listed in table 2

Table 2 Parameters imported into the Platform module from the Constants and Utilities worksheet.

Parameter	**Source**	**Symbol**	**Units**
Satellite speed	Const and Util C15	V_S	km/s
Earth radius	Const and Util C14	R_e	km
Average earth radius	Const and Util C18	$\langle R_e \rangle$	km
Average satellite speed	Const and Util C19	$\langle V_S \rangle$	km/s
Equatorial squint angle	Const and Util C20	ε_e	deg
New orbit period	Const and Util G46	T_{New}	min

3.1.2 Calculations

The calculations contained in this module serve two roles: they provide inputs for other modules and they allow the user to explore gross orbit properties and spacecraft azimuth steering requirements. Some of the exploration (local) variables are not exported so that they can be manipulated without affecting other results. In the detailed descriptions, the parameter equations are keyed to spreadsheet location.

The variables calculated in this module, their location, symbols and units are listed in Table 3.

Table 3 Parameters calculated in the Platform Module.

Parameter	**Symbol**	**Units**	**Location**
Sub-satellite point speed	V_{sub}	km/s	I11
Satellite period	T	Min	I12
Orbits per day	N_O		I13
Maximum orbit latitude	θ_{Max}	Deg	I14
Orbit central angle	C_P	Deg	I15
Time from ascending node	t_P	Min	I16
Mechanical azimuth squint	ε_P	Deg	I17
Orbit type	S_O		H18,I18
Longitude shift/orbit period	Δ	Deg	I19
Orbit track angle	χ_P	Deg	I20
New orbit period	T_{New}	Min	I21
Required satellite altitude	N_{New}	Km	I22

I11 Sub-Satellite Point Speed

The sub-satellite point speed defines the speed at which the projection of the satellite position onto the earth's surface moves along the satellite track. V_{sub} calculated in I11 is a local variable.

$$V_{sub} = V_S \frac{R_e}{R_e + H}$$

V_{sub} is a global variable

I12 Satellite Period

The satellite period is the time in minutes for the satellite to complete an orbit.

$$T = \frac{2\pi \langle R_e \rangle}{60 \langle V_S \rangle}$$

T is a global variable

I13 Orbits per day

$$N_O = \frac{1440}{T}$$

N_O is a local variable

I14 Maximum orbit latitude

The maximum orbit latitude is defined by the orbit inclination angle measured counter-clockwise from the equator to the ascending node satellite velocity vector. This latitude defines the north and south extremes of the satellite orbit track.

$$\theta_{Max} = Min(i, 180 - i)$$

θ_{Max} is a global variable

I15 Orbit central angle

The progression of the satellite around its orbit is measured as the angle between the ascending node (north-bound equator crossing) and the current satellite position. The apex of this angle is located at the centre of the earth and the plane of the angle is the orbit plane.

$$C_P = \sin^{-1}\left(\frac{\sin(\theta_S)}{\sin(i)}\right) + 180\frac{(1-S_N)}{2} + 360\frac{(1-S_N S_H)(1+S_N)}{4}$$

Transitions between degrees and radians have been left out of the equation but must be present in the EXCEL implementation. The switch $(1-S_N)/2$ is on (has value 1) for descending node positions only and the switch
$[(1-S_N S_H)/2][(1+S_N)/2]$ is only on for the ascending orbit quadrant that is south of the equator.

C_P is a local variable

I16 Time from ascending node

The elapsed time from the ascending node to the current satellite position is:

$$t_P = T\frac{C_P}{360}$$

where t_P is a local variable in minutes.

I17 Mechanical Azimuth Squint

The rotation of the earth generates a systematic Doppler offset in space-based SAR data. This offset varies with the central angle of the orbit, has its maximum value when the satellite crosses the equator and is zero at the north and south extreme latitudes. The earth rotation Doppler can be approximately corrected by dynamically squinting the radar beam to add a component of the satellite velocity to the total observed Doppler shift. This squint is currently introduced by dynamically rotating the satellite in azimuth as it proceeds around the orbit. In future satellite generations it may be implemented by electronic steering.

$$\varepsilon_P = \varepsilon_e \cos(C_P)(2Ceiling(\frac{i}{90}, 1) - 3)$$

Here, the switch (2Ceiling(i/90,1)-3) is set to 1 (squint toward the direction of satellite motion) for retrograde orbits and is set to –1 (squint away from the direction of satellite motion) for prograde orbits.

ε_P is a local variable in degrees.

H18,I18 Orbit type

If the inclination of an orbit is greater than 90 degrees, the satellite progresses around the orbit in the direction opposite to the earth rotation. This is a retrograde orbit. For a prograde orbit the inclination angle is less than 90 degrees and the satellite motion has a component in the earth rotation direction.

$$IF(i > 90,'retrograde\_orbit', else,' prograde\_orbit');.......S_O = 2Ceiling(\frac{i}{90},1) - 3$$

The switch S_O has value 1 for retrograde orbits and value –1 for prograde orbits.

S_O is a global variable

I19 Longitude shift per orbit period

The satellite orbit plane is controlled to rotate with the sun-earth line over the course of a year. The geographic position of a satellite at successive ascending nodes is determined by the earth rotation over an orbit period. The relative longitude shift is Δ.

$$\Delta = \frac{15T}{60}$$

Δ is a local variable in degrees.

I20 Satellite track angle

The satellite track angle is the satellite direction of travel measured clockwise from north.

$$\chi_P = 360(1+S_O)/2 - 180S_O(1-S_N)/2 + \tan^{-1}\left(\frac{1}{\cos(C_P)\tan(i)}\right)$$
$$+180\frac{(1+S_H)(1-S_N)}{4}Floor(\frac{\theta_S}{\theta_{Max}},1) - 180\frac{(1-S_H)(1+S_N)}{4}Floor(\frac{\theta_S}{\theta_{Max}},1)$$

The functions: $180(1+S_H)(1-S_N)Floor(\theta_S/\theta_{Max},1)/4$ and $180(1-S_H)(1+S_N)Floor(\theta_S/\theta_{Max},1)/4$ provide point corrections for the odd-order singularities of the inverse tangent function at 90^0 and 270^0. The other switch functions are used to extend the inverse tangent output around the 0^0 to 360^0 range.

χ_P is a local variable in degrees.

I21 New Orbit period

T_{New} has been estimated from the orbit repeat cycle constraint in the Constants and Utilities Module. It is the orbit period required to provide the selected repeat cycle.

I22 Required satellite altitude

The orbit period can only be changed by changing the orbit altitude. The history of planned altitude changes over the satellite lifetime becomes a line entry in the on-board fuel budget. H_{New} is computed but is not automatically linked to calculations. Operator input of H_{New} to E10 (H) is required to propagate the impact of an orbit repeat cycle selection to other spreadsheet calculations.

$$H_{New} = \left(\frac{60 T_{New} 631.3481}{2\pi} \right)^{2/3} - < R_e >$$

3.2 Control Sheet “Observation Geometry” Module

The “Observation Geometry” module: models spherical earth relationships between the satellite and a point on the earth surface that is observed by the SAR at a specified incidence angle; models the relationship between a selected radar swath and the satellite; and models swath and resolution cell parameters.

The inputs to this module are the target and swath parameters:
- Geographic target position,
- Target incidence angle,
- Radar incidence angle range
- Swath width and near edge incidence angle
- Range resolution and over-sampling ratio

The parameters calculated in this module are grouped into three display blocks:
- Computed Satellite Values
- Computed Target Values
- Computed Swath Values

All calculations are based on strip-mapping SAR and locally spherical earth assumptions.

3.2.1 Inputs

The input variables used in this module, their symbols and units are listed in Table 4.

With the exception of the longitude switch, the selector switches use the algorithm Exx=3-2Cxx to generate the ±1 switch state used in the calculation software. The longitude selector uses the algorithm Exx=2Cxx-3. The switch activator is an EXCEL “Combo box’. The increment switch activators use an EXCEL “spinner’ to successively increment the output variables in 31 steps. The algorithm for both controls is $\psi_x = Cyy(\psi_{Max} - \psi_{Min})/30$.

The target position parameters are used to explore imaging geometry and observation timing issues.

Table 4 User Input parameters for the Observation Geometry module.

Parameter	Type	Symbol	Units	Cells
Target latitude	User Input	θ_T	deg	E27
Hemisphere (N/S)	Selector switch	S_H		C29,E29
Target longitude	User Input	ξ_T	deg	E31
Hemisphere (E/W)	Selector switch	S_E		C32,E32
Look direction	Selector switch	S_L		C34.E34
Pass segment	Selector switch	S_N		C35,E35
Minimum incidence angle	User Input	ψ_{Min}	deg	E37
Maximum incidence angle	User Input	ψ_{Max}	deg	E38
Swath width	User Input	D	km	E39
Range resolution	User Input	ρ_R	m	E40
Range definition	Selector switch	S_ρ		C41,E41
Target incidence angle	Increment switch	ψ_T	deg	C43.E43
Swath near edge incidence	Increment switch	ψ_D	deg	C44,E44
Range over-sampling ratio	User input	OSR		E46
Constrain bandwidth	Selector switch	S_B		C47,E47
Bandwidth constraint	User Input	B	MHz	E49

Variables imported from other worksheets are listed in Table 5.

Table 5 Parameters imported into the Observation Geometry Module from the Constants and Utilities worksheet

Parameter	Source	Symbol	Units
Speed of light	Const and Util C5	c	m/s
Length of day	Const and Util C9	M	s.
Local earth radius	Const and Util C14	R_e	km
Equatorial azimuth squint	Const and Util C20	ε_e	deg.
First quadrant beam angle	Const and Util D49	γ_1	deg.
First quadrant latitude offset	Const and Util D50	θ_1	deg
First quadrant orbit centre angle	Const and Util D53	C_1	deg

3.2.2 Observation Geometry Module Calculations

In the spreadsheet, the Observation Geometry calculations are presented in three groupings:

- Computed Satellite Values
- Computed Target Values

- Computes Swath Values.

The Observation Geometry module has been designed to allow the user to explore different combinations of radar modes and settings. The calculations in this module are linked through the rest of the spreadsheet to allow the implications of the input combinations to be assessed. By iterating selected parameter combinations “best choices” of some interdependent parameter sets can be deduced.

The parameters used in The “Computed Satellite Values” grouping are listed in Table 6. This Parameter set is based on knowledge of the Earth surface point of interest and the incidence angle at which it is imaged. The parameters used in the “Computed Target Values” grouping are listed in Table 7 and the parameters used in the “computed Swath Values” grouping are listed in Table 8. In the detailed descriptions that follow each table, the formulae used for each entry are described in their order of occurrence in the spreadsheet and are linked to the spreadsheet cell numbers.

3.2.2.1 Computed Satellite Values

Table 6 Computed parameters in the Computed Satellite Values group

Parameter	**Symbol**	**Units**	**Location**
Beam squint	ε	deg	I27
Target azimuth from satellite	γ	deg	I28
Satellite latitude offset from target	θ_Δ	deg	I29
Satellite longitude offset from target	ξ_Δ	deg	I30
Satellite latitude	θ	deg	I31
Satellite longitude	ξ	deg	I32
Orbit central angle	C	deg	I33
Orbit time from ascending node	T	min	I34
Unwrapped longitude to ascending node	ξ_U	deg	I35
Ascending node longitude	ξ_A	deg	I36
Solar time from ascending node	T_{sol}	min	I37
Satellite track angle	χ	deg	I38
Previous track longitude at satellite latitude	ξ_{-1}	deg	I39
Next track longitude at satellite latitude	ξ_{+1}	deg	I40
Track separation at satellite latitude	D_{TR}	km	I41
Slant range resolution	ρ_R	m	I43
Bandwidth	B	MHz	I44
Ground range resolution	ρ_G	m	I45
Range sample interval	δ	m	I46
Samples/slant range swath	N_S		I47

I27 Beam Squint

The beam squint is calculated from the equatorial squint and the orbit centre angle. Its sign is set by condition switches to compensate for the relative earth rotation direction. When the radar beam is pointed normal to the satellite track (RADARSAT 1 case) the squint is 0^0.

$$\varepsilon = \varepsilon_e \cos(C) S_N S_O S_S$$

I28 Target azimuth from the satellite

The Target azimuth is the north angle (measured clockwise from north) of the vector from the satellite to the target as measured at the satellite.

$$\gamma = (\gamma_1 - \varepsilon) S_N + 360(1 - S_N)/2$$

I29 Satellite latitude offset from the target

The Satellite is offset from the target by a latitude increment θ_Δ using the imported parameter θ_1 that is squint corrected using the earth centre angle, α_t, calculated in the Computed Target Values group.

$$\theta_\Delta = \theta_1 + \alpha \sin(\varepsilon)$$

I30 Satellite longitude offset from the target

The satellite is offset from the target by a longitude increment, $\xi_{\Delta.}$ This calculation uses the earth centre angle to the target, α, that is calculated in the Computed Target Values group.

$$\xi_\Delta = \tan^{-1}(\tan(\alpha)\sin(\gamma))$$

I31 Satellite latitude

Note: High inclination orbits allow the radar to see over the north or south pole (which one depends on the look direction and on the orbit type). This program calculates the smallest satellite latitude at which these targets are visible and does not trace the transpolar target observation conditions.

The satellite latitude is estimated from the input target latitude.

$$\theta = \theta_T S_N + \xi_\Delta$$

I32 Satellite longitude

The satellite longitude is estimated from the target longitude. Condition switches are used to determine sign and the longitude singularity at ±180 degrees is corrected using the switch: Floor(($\xi_T S_E + \xi_\Delta$)/180,1)) which is 0 unless the longitude computed internally exceeds 180 degrees.

$$\xi = (\xi_T S_E - \xi_\Delta S_O)(1 - Floor(ABS(\xi_T S_E + \xi_\Delta)/180,1))$$
$$+ S_N S_E (360 - ABS(\xi_T S_E + \xi_\Delta)) Floor(ABS(\xi_T S_E + \xi_\Delta)/180,1)$$

I33 Orbit Central Angle

The orbit central angle is generated from the result of a truncated iteration that relates satellite position parameters to the target position and incidence angle. The approximation is quite good over most of its range but has approximately $\pm 0.4^0$ accumulated error as the satellite approaches the next ascending node from the south.

$$C = IF(C_1 < 0.04, 180\frac{1-S_N)}{2} + 360\frac{(1+S_N)(1-S_H)}{4}, Min(C_1 S_N S_H + 180\frac{1-S_N)}{2}$$

$$+360\frac{(1+S_N)(1-S_H)}{4} + 360\left(1 - \frac{C_1 S_N S_H + 180\frac{1-S_N)}{2} + 360\frac{(1+S_N)(1-S_H)}{4}}{ABS(C_1 S_N S_H + 180\frac{1-S_N)}{2} + 360\frac{(1+S_N)(1-S_H)}{4})}\right)/2,$$

$$360.2))$$

The IF statement follows the EXCEL protocol: IF(A, execute if A is true, execute if A is false).

I34 Orbit time from ascending node

The time in minutes from the ascending node is defined by the orbit central angle and the satellite period.

$$t = \frac{CT}{360}$$

I35 Unwrapped longitude from the ascending node

The unwrapped longitude from the ascending node is an absolute angle computed past the $\pm 180^0$ singularity.

$$\xi_U = 180(Floor(\frac{C}{90},1) - Floor(\frac{C}{180},1)) + \tan^{-1}(\tan(C)\cos(\theta_{Max})) + \frac{15tS_O}{60}$$

Here the first function takes values 0^0, 180^0, 360^0 in quadrants: 1, 2 and 3, 4 respectively. The last function corrects for earth rotation using a 15^0/h rotation rate definition.

I36 Ascending node longitude

The ascending node longitude is back-projected from the satellite longitude,

$$\xi_A = 360 S_O Floor((\xi - \xi_U S_O)/180,1) + \xi - \xi_U S_O + 360 Floor((\xi - \xi_U S_O)/360,1)(1 - S_O)/2$$

I37 Solar time from ascending node

The solar time in hours from the ascending node gives the relative local time at the satellite position and, thus, the local time at which the target is observed.

$$T_{Sol} = ((\xi_U - \frac{S_O t_A}{4})(1 - Floor((\xi_U - \frac{S_O t_A}{4})/180,1))(1 - Floor((\xi_U - \frac{S_O t_A}{4})/359.999,1))$$

$$+ (360 - \frac{S_O t_A}{4}) Floor((\xi_U - \frac{S_O t_A}{4})/180,1))/15$$

I38 Satellite track angle

The satellite track angle is the angle measured clockwise from north that defines the satellite direction of travel.

$$\chi = 360(1 + S_O)/2 + S_O 180(1 - S_N)/2 + \tan^{-1}\left(\frac{1}{\cos(C)\tan(i)}\right)$$

I39 Previous track longitude at the satellite latitude

This is the satellite longitude when it was at the satellite latitude during the previous pass.

$$\xi_{-1} = \xi - S_O \frac{T}{4}$$

I40 Next track longitude at the satellite latitude

This will be the satellite longitude when it crosses the satellite latitude during the next pass.

$$\xi_{+1} = \xi + \frac{S_O T}{4} - 360 Floor(ABS(\xi + \frac{S_O T}{4})/180,1) S_E$$

I41 Track separation at the satellite latitude

This parameter gives the distance in km between adjacent satellite tracks and provides an indication of regions that may be visible on two successive passes.

$$D_{TR} = ABS(2\pi R_e \frac{\xi_{-1} - \xi}{360} \cos(\theta))$$

I43 Slant range resolution

The slant range resolution of the radar is defined by the radar bandwidth and is a fundamental instrument parameter. The spreadsheet inputs define three possible inputs that generate the same value: the slant range resolution, the ground range resolution and the radar bandwidth.

$$\rho_R = (\rho_R (1 + S\rho)/2 + \rho_R \sin(\theta_{Min})(1 - S_\rho)/2)(1 + S_B)/2 + 1000000cB(1 - S_B)/2$$

I45 Ground range resolution

The ground range resolution is traditionally defined as the projection of the range resolution onto the local geoid. As in I43, the parameter must be derived from three possible inputs.

$$\rho_G = (\rho_R(1 - S_\rho)/2 + \frac{\rho_R}{\sin(\psi_T)}(1 + S_\rho)/2)(1 + S_B)/2 + \frac{\rho_R}{\sin(\psi_T)}(1 - S_B)/2$$

I46 Slant range sample interval

The slant range sample interval is the range pixel spacing in m.

$$\delta = \frac{\rho_R}{OSR}$$

I47 Samples/slant range swath

The number of range samples in the slant range swath is calculated from the selected slant range swath width generated in the Computed Swath Values group.

$$N_S = \frac{1000 d_{SR}}{\delta}$$

I44 Bandwidth

The radar bandwidth in MHz is half of the speed of light in m/μs divided by the slant range resolution.

$$B = \frac{150}{\rho_R}$$

3.2.2.2 Computed Target Values

Table 7 Parameters calculated in the Computed Target Values group.

Parameters	**Symbol**	**Units**	**Location**
Target visible to the radar			N27
Local earth radius	R_e	km	N28
Earth surface rotation speed	v_e	M/s	N29
Target illumination angle	β_T	deg	N30
Target earth centre angle	α	deg	N31
Target offset from satellite track	d_T	km	N32
Target slant range	R	km	N33
Target illumination time	T_t	S	N34

N27 Target visibility

When the target latitude approaches or exceeds the maximum satellite orbit latitude, the target may, or may not, be visible to the radar at its specified incidence angle.

$$a = IF(\theta_T < Min(i, 180 - i) + \alpha S_N S_H S_O, YES, NO)$$

N28 Earth radius

The earth radius, R_e is imported from the ‘Const and Util’ worksheet. R_e is calculated from the target latitude entered in the Observation Geometry module.

N29 Earth surface rotation speed

This is the linear speed (m/s) of the geoid surface in the direction of the earth rotation at the target latitude.

$$v_s = \frac{2000\pi R_e \cos(\xi_T)}{M}$$

N30 Target illumination angle

The target illumination angle is the angle between the range vector to the target and the satellite nadir as measured at the satellite.

$$\beta_T = \sin^{-1}\left(\frac{R_e \sin(\psi_T)}{R_e + H}\right)$$

N31 Target earth centre angle

This is the angle formed at the centre of the earth by the satellite and target positions.

$$\alpha = \xi_T - \beta_T$$

N32 Target offset from satellite track

This is the distance in km from the sub-satellite point to the target measured along the great circle arc connecting the two points.

$$d_T = \alpha R_e$$

N33 Target slant range

This is the range in km from the radar to the target.

$$R = \sqrt{R_e^2 + (R_e + H)^2 - 2R_e(R_e + H)\cos(\alpha)}$$

N34 Target illumination time

The synthetic aperture is often taken to be the time in seconds that the target illumination lies within –3 dB of the illuminating beam centre.

$$T_t = \frac{R\varphi_{A1}}{V_{sub}}$$

3.2.2.3 Computed Swath Values

Table 8 Calculated parameters in the Computed Swath Values group.

Parameter	Symbol	Units	Location
Earth centre angle to far swath edge	α_f	deg	N37
Earth centre angle to near swath edge	α_n	deg	N38
Surface distance to access the far edge	d_f	km	N39
Surface distance to access the near edge	d_n	km	N40
Maximum adjacent pass overlap (opposite look)	d_o	km	N41
Access swath width	D_A	km	N42
Range to near edge of far swath	R_f	km	N43
Incidence angle, near edge, far swath	ψ_f	deg	N44
Selected swath near edge offset angle	α_{Sn}	deg	N45
Selected swath near edge offset distance	d_{Sn}	km	N46
Selected swath near edge slant range	R_{Sn}	km	N47
Selected swath ground range width	D_{SG}	km	N48
Selected swath slant range width	D_{SR}	km	N49
Selected swath far edge incidence angle	ψ_{Sf}	deg	N50

N37 Earth centre angle to the far swath edge

This is the angle in degrees formed at the earth centre by the sub-satellite point and the far edge of the far swath.

$$\alpha_f = \psi_{Max} - \sin^{-1}\left(\frac{R_e \sin(\psi_{Max})}{R_e + H}\right)$$

N38 Earth centre angle to the near swath edge

This is the angle in degrees at the centre of the earth between the sub-satellite point and the near edge of the near swath.

$$\alpha_n = \psi_{Min} - \sin^{-1}\left(\frac{R_e \sin(\psi_{Min})}{R_e + H}\right)$$

N39 Surface distance to access far edge

This is the great circle (normal) distance in km. on the geoid from the sub-satellite point to the far edge of the far swath.

$$d_f = \alpha_f R_e$$

N40 Surface distance to access near edge

This is the great circle (normal) distance in km. on the geoid from the sub-satellite point to the near edge of the near swath.

$$d_n = \alpha_n R_e$$

3.3 Control Sheet "Antenna" Module

The Antenna module accepts high-level parameters that describe the radar antenna and accepts some guesses at key parameters that influence the antenna performance. Additional antenna parameters and antenna performance parameters are modeled under the assumption that the antenna aperture is uniformly illuminated and that no "phase spoiling' is used for beam control. The minimum partitioning of the antenna into an active-array architecture is then computed using parameters generated in the "Radar" module. The Antenna module is partitioned into two groupings:

- Antenna Properties
- Active Array parameters

The calculations in the Antenna properties group treat the antenna as a whole and estimate gains and beam widths as well as the boresight angle and antenna steering requirements. The calculations in the Active Array Parameters group consider the antenna as an assembly of transmit-receive sub-arrays and estimates their gross properties.

3.3.1 Inputs

The variables input to the Antenna module are listed in Table 9.

Table 9 Input parameters for the Antenna module.				
Parameter	**Type**	**Symbol**	**Units**	**Cells**
Wavelength/frequency	Selector switch	S_W		C56,E56
Wavelength/frequency	User input	λ, f	m, MHz	E57
Antenna length	User Input	L	m	E58
Antenna width	User Input	W	m	E59
Number of apertures	User Input	N_A		E60
Number of polarizations	User Input	N_P		E61
Number of panels	User Input	N_{pan}		E62
Radiation efficiency	User Input	η_A		E63
Feed loss	User Input	L_{feed}	dB	E64
Boresight calculate/input	Selector switch	S_{Bor}		C65,E65
Boresight angle	User Input	β_A	deg	E66
Elevation row calculate/input	Selector switch	S_{ER}		C67,E67
Number of elevation rows	User Input	N_E		C68
Array size calculations	Selector switch	S_P		C69,E69
Input number of TR modules	User Input	N_{TR1}		E70

In Table 9, the Wavelength/frequency switch defines the parameter type for the following entry. The “Boresight calculate/input” switch and the “Elevation row calculate/input” switches both allow the following user inputs to override calculated values. The “Array size calculations” switch allows the user:

- to specify the number of TR modules,
- to specify that the minimum power used to define the array is calculated from the reference point (E13)
- to specify that the minimum power used to define the array is calculated from the current, selected swath.

The switch implementations use EXCEL “Combo box” tools to load an integer into the hidden column C and create the ±1 (and –3 for S_P) switch signals with the algorithm Exx=3-2Cxx where (xx) is a cell number in table 9. The switch S_P allows the user to lock the radar configuration to a user input so that swath-dependent properties can be explored.

Table 10 lists the parameters imported from the constants and utilities worksheet

Table 10 Parameters imported into the Antenna module from other work sheets.			
Parameter	**Source**	**Symbol**	**Units**
Speed of light	Const and Util C5	C	m/s

3.3.2 Parameters calculated in the Antenna module

3.3.2.1 Antenna Properties

The Antenna Properties group of the Antenna module computes functional antenna parameters from User Inputs and from parameters calculated elsewhere in the spreadsheet. The parameter set calculated in this group is listed in Table 11.

Table 11 Parameters calculated in the Antenna Properties group.

Parameter	**Symbol**	**Units**	**Location**
Wavelength	λ	M	I55
Frequency	F	GHz	I56
Maximum antenna gain (1 way)	G		I57
Maximum antenna gain (1 way)	G_d	DB	I58
Gain/aperture	G_{ap}		I59
Azimuth beamwidth (1way)	φ_{A1}	Deg	I60
Elevation beamwidth (1way)	φ_{E1}	Deg	I61
Elevation beamwidth (2 way)	φ_E	Deg	I62
Beamwidth for swath coverage	φ_S	Deg	I63
Elevation boresight	β_E	Deg	I64
Elevation steering range	ϕ	Deg	I65
Fractional bandwidth	F_B		I66
Antenna area	a_{Ant}	m^2	I67

I55 Wavelength

Depending on the input selection the radar wavelength is either an input parameter or is computed from the radar frequency.

$$\lambda = \frac{c}{1000000000f}(1 - S_W)/2 + \lambda(1 + S_W)/2$$

I56 Frequency

Depending on the input selection, the radar frequency in GHz is either an input variable or is calculated from the wavelength

$$f = f(1 - S_W)/2 + \frac{c}{1000000000\lambda}(1 + S_W)/2$$

I57 Antenna gain

The antenna gain is calculated for a uniformly weighted aperture (sinc^2 power radiation pattern).

$$G = \frac{4\pi LW}{\lambda^2}$$

I58 Antenna gain

The antenna gain is calculated for a uniformly weighted aperture (sinc^2 power radiation pattern).

$$G = \frac{4\pi LW}{\lambda^2}$$

I58 Antenna gain

The antenna gain expressed in dB is

$$G_d = 10Log10(G)$$

I59 Gain per aperture

When the antenna is configured as N_A equal apertures the gain of each aperture is:

$$G_{ap} = \frac{G}{N_A}$$

This configuration is used for MTI applications and is not pursued further in this version of the spreadsheet.

I60 Azimuth beam width (1 way)

The one-way beam width (-3 dB) refers to either the transmitting or the receiving path. When both transmit and receive paths are combined the effective antenna pattern is said to be a two-way pattern. In the simplest case, the same antenna is used for both functions and the two-way gain is the square of the 1 way gain, otherwise the two-way gain is the product of the one-way transmit and receive gains.

$$\varphi_{A1} = \frac{0.88\lambda}{L}$$

I61 Elevation beam width (1 way)

The elevation beam width (-3dB) is estimated for a uniformly illuminated aperture.

$$\varphi_{E1} = \frac{0.88\lambda}{W}$$

I62 Elevation Beam width (2 way)

The scaling constant assumes a uniformly weighted aperture and relates the half power width of a sinc^4 function to that of a sinc^2 function.

$$\varphi_E = 0.721406\varphi_{E1}$$

I63 Beam width for swath coverage

The -3 dB elevation beam width needed to cover the specified swath can be estimated by the swath width, incidence angle and slant range. When beam shaping is allowed and is needed to provide reasonable illumination, this parameter can be used to provide a first order estimate of the resulting antenna gain.

$$\varphi_S = \frac{D\cos(\psi_D)}{R_{\mathrm{Re}\,f}}$$

I64 Elevation boresight

The elevation boresight angle is the angle between the normal to the antenna face and the nadir as measured at the satellite. Depending on input selections this is either an input parameter or is calculated from the reference incidence angle.

$$\beta_E = \beta_A(1 + S_{ER})/2 + \sin^{-1}\left(\frac{R_e\sin(\psi_R)}{R_e + H}\right)(1 - S_{ER})/2$$

I65 Elevation steering range

The elevation beam is electronically steered from the illumination angle corresponding to the minimum incidence angle to the illumination angle corresponding to the maximum incidence angle. The steering angle range is selected to suppress grating lobes due to the discrete nature of the array. The maximum angle from boresight defines the steering angle range.

$$\phi = Max(\psi_{Max} - \alpha_f - \beta_E \ , \beta_E - \psi_{Min} + \alpha_n)$$

I66 Fractional bandwidth

The fractional bandwidth is the ratio between the bandwidth and the radar frequency. The size of the ratio has a direct bearing on the antenna radiator designs that can be considered for antenna implementation. When the fractional bandwidth exceeds 5% the use of resonant elements such as patch radiators becomes tricky and other radiator designs should be considered.

$$F_B = \frac{B}{f}$$

I67 Antenna Area

$$a_{Ant} = LW$$

3.3.2.2 Active Array Parameters

The Active Array parameters' calculations use the antenna properties and parameters computed in the Radar module to define the minimum array partition that will meet the radar specifications. The parameter set calculated in this group is listed in Table 12

Table 12 Parameters calculated in the Active Array group.

Parameter	Symbol	Units	Location
Elevation row spacing (wavelengths)	w_e		N55
Number of rows in elevation	N_R		N56
Minimum transmitter power	P_{Min}	W	N57
Minimum number of TR modules	N_{TR}		N58
TR modules/panel	N_{Tp}		N59
Minimum number of azimuth radiators/panel	N_{Pa}		N60
Radiators/TR	N_T		N61
Radiator azimuth spacing (wavelengths)	w_a		N62
Azimuth sub-array length	L_{sa}	m	N63
Azimuth sub-array beam width	φ_{sa}	deg	N64
Maximum electronic azimuth steering angle	ϕ_A	deg	N65
Total number of radiators	N_{Rad}		N66

N55 Elevation row spacing in wavelengths

The maximum spacing (in wavelengths) of the phase-controlled rows of antenna radiators is determined by the grating lobe onset at the maximum elevation steering range.

$$w_e = \frac{1}{1 + \sin(\phi)}$$

N56 Number of rows in elevation

The minimum number of rows that can be used without exciting grating lobes at the maximum steering angle is selected to provide row spacing less than w_e. This number can be over-ridden by operator selection and is only used in subsequent calculations if the operator allows free calculation.

$$N_R = Ceiling\left(\frac{W}{w_e \lambda}, 1\right)$$

N57 Minimum transmitter power

The default for this spreadsheet is the aperture-limited antenna gain, however, if the swath is significantly wider than the aperture-limited elevation beam, a swath limited gain is more appropriate (shaped beam case). The relative power at the swath edge, P_{rel}, is used to determine which value is appropriate. This program works with the minimum transmitter power that satisfies all specifications. The value appearing in this cell must be exceeded in the design for the radar to meet all specifications. When operator selections force the array design to non-optimum values, the discrepancy will appear as a negative power margin in cell N83.

$$P_{\min} = IF(P_{rel} < 0.25, P_{\sigma}, P_{A})$$

N58 Number of TR modules

The minimum number of TR modules that deliver at least the minimum power is determined by an integer calculation that includes all known constraints. The setting of the switch S_P determines whether the array is calculated using reference-point or swath estimates of the minimum required power and determines whether a manual over-ride has been applied.

$$N_{TR} = IF\left(S_P = -3, N_{TR1}, Ceiling\left(\frac{Ceiling\left(\frac{Ceiling\left(\frac{(P_A(1+S_P)/2 + P_\sigma(1-S_P)/2)}{P_{TR}},1\right)}{N_R(1+S_{ER})/2 + N_E(1-S_{ER})/2},1\right)}{N_{Pan}},1\right)\right)$$

N59 TR modules /panel

The antenna architecture is rows of radiators forming columns on each panel. Each row on each panel will have one or more TR modules. The number of TR modules on each panel is :

$$N_{Tp} = \frac{N_{TR}}{N_{Pan}}.$$

N60 Minimum number of azimuth radiators/panel

The radiators are organized into azimuth-oriented sub-arrays. Each sub-array is connected to one TR module. There may be several sub-arrays across a panel.

$$N_{Pa} = Ceiling\left(\frac{L}{N_{Pan}\lambda},1\right)$$

N61 Radiators/TR

Each TR module will be connected to several TR modules.

$$N_T = Ceiling\left(\frac{N_{Pa}N_R}{N_{Tp}},1\right)$$

N62 Radiator Azimuth spacing

The radiator spacing in the azimuth direction (in wavelengths) is determined by the total number of radiators and the length of the antenna. This spacing becomes important if electronic steering is used in the azimuth direction.

$$w_A = \frac{L}{\lambda N_P N_T \dfrac{N_{Tp}}{(N_E(1-S_{ER})/2 + N_R(1+S_{ER})/2)}}$$

N63 Azimuth sub-array length

Each sub-array has length L_{sa} m.

$$L_{sa} = \frac{LN_T}{N_{Pan}N_{Pa}}$$

N64 Azimuth sub-array beam width

The sub-array beam width is calculated using a uniform-illumination assumption. The computed angle is in radians and is reported in the spreadsheet in degrees.

$$\varphi_{sa} = \frac{0.88\lambda}{L_{sa}}$$

N65 Maximum azimuth electronic steering angle

The spreadsheet uses the rule-of-thumb that an array of arrays can be phase steered without serious grating problems within a quarter of the sub-array beam width. When the resulting angle is within a factor of two of the mechanical steering angle used to minimize earth rotation effects, doubling the number of TRs and using electronic steering may be a cost-effective option to mechanically pointing the satellite.

$$\phi_A = 0.25\varphi_{sa}$$

N66 Total number of radiators

This is the total number of radiating elements (patches, dipoles, etc) on the antenna.

$$N_{Rad} = N_{TR} N_T$$

3.4 Control sheet “ Radar” Module

The radar module accepts a number of user inputs that provide a basic description of key signal and system parameters and calculates the minimum transmitter power, range ambiguity properties, receiving window length and timing limits, data volumes and basic image properties. The first order model contained in this spreadsheet concentrates on the radar sensor and does not include major components of the radar processor required to generate images. Sensor details that are based on design budgets are also excluded as they belong to the next design iteration.

The Radar module is divided into 5 groups:

- Specification Point Calculations
- Selected Swath Calculations
- Data handling calculations
- Downlink
- Image properties.

“Specification Point Calculations” are based on an incidence angle (E13) at which the basic radar specifications are deemed to be valid. This angle is often extractable from initial specifications. “Selected Swath Calculations” use data from the swath incidence angle selector in the Observation Geometry module to define the power calculation conditions. The Data handling group deals with computed data volumes. The Downlink group deals with the effect of link constraints. The image properties group summarizes selected properties of SAR images acquired by the radar as these are inferred from first-order model calculations.

3.4.1 Inputs

The user inputs to the Radar module are summarized in Table 13. Firm values are used where possible and the rest are reasonable guesses based on current technology and experience with known systems.

Table 13 User inputs to the Radar Module.

Parameter	Type	Symbol	Units	Cells
Chirp length (micro-seconds)	User Input	τ		E75
Noise equivalent sigma_0	User Input	σ^0_{NE}		E76
Receiver noise figure	User Input	F_N	dB	E77
Electronics temperature	User Input	T_e	K	E78
Azimuth over-sampling ratio	User Input	OSA		E79
TR power	User Input	P_{TR}	W	E80
Range ambiguity	User Input	p_{Amb}	dB	E81
Acceptable margin	User Input	Ma	dB	E82
ADC quantization (I, Q)	User Input	Q	Bits	E83
Auxiliary data block	User Input	A_x	Bits	E84
Data recorder capacity	User Input	T_{rec}	Bits	E85
Down-link channel capacity	User Input	C_{ap}	B/s	E86
Number of down-link channels	User Input	N_C		E87
Encryption overhead	User Input	E	%	E88

A number of parameters merit a brief explanation. The ”Noise-equivalent sigma_0” entry refers to the terrain radar cross-section for which the instrument signal-to-noise ratio is 1.0. It is a measure of the self-generated radar noise but does not include phase-noise effects that result from timing jitter and oscillator phase instability. The “Electronics temperature” is the physical temperature of the radar receiver electronics and, in particular, the first amplifier stage. The “TR power” is the microwave power output of the transmitter part of a single Transmit-Receive module. The “Range ambiguity” is the specified maximum relative power returned from more distant terrain surfaces illuminated by previous pulses that are superimposed on the desired signal. The “Acceptable margin” is a reference note that indicates the desirable ratio between minimum performance that meets specification and actual performance in early design stages. This parameter is not used in calculation. The “ADC quantization” is the number of bits available for each of the In-phase and Quadrature signal components in the digital output of the receiver. The “Auxiliary data block” is an estimate of the volume of sensor setting and other system data that is included with each swath of digitized radar returns.

The Radar module makes use of a number of parameters that are imported from other worksheets. These are listed in Table 14.

Table 14 Parameters imported into the Radar module from the Constants and Utilities worksheet.

Parameter	Source	Symbol	Units
Speed of light	Const and Util C5	c	m/s
Boltzman's constant	Const and Util C6	K	W/K/s
Sinc^4	Const and Util G32		
Sinc^2	Const and Util G39		
Summed range ambiguity	Const and Util O10	P_{amb}	

3.4.2 Parameters calculated in the Radar module

3.4.2.1 Specification Point Calculations

The Specification Point Calculations are derived from conditions deemed to be valid at the reference incidence angle (E13) in the Platform module input set. The calculations are based on the assumption that specified performance must be equaled or exceeded.

The parameters computed in the Specification Point Calculations are listed in Table 15

Table 15 Parameters computed in the "Specification Point Calculations" group

Parameter	Symbol	Units	Location
Minimum pulse repetition frequency	f_{PR}	Hz	I75
Slant range to data reference	R_{ref}	km	I76
Real aperture area	A_{RA}	m^2	I77
Noise temperature	T_N	K	I78
Beam shaping feasible?			I79
3 dB swath width	D_3	km	I80
Minimum peak power (beam centre)	P_{bc}	W	I81
Relative power at the swath edge	p_{rel}		I82
Adjusted minimum peak power	P_A	W	I83
Peak transmitter power	P_T	W	I84
Transmitter power design margin	p_{marg}	dB	I85
Range distance to first ambiguity	d_A	km	I86
First ambiguity slant range	R_{A1}	km	I87
Earth center angle at first ambiguity	α_{A1}	deg	I88
Incidence angle at first ambiguity	ψ_{A1}	deg	I89
First ambiguity angle from boresight	β_{A1}	deg	I90
Relative received power from first amb.	p_{A1}		I91
Relative range ambiguity (dB)	A1	dB	I92

I75 Minimum Pulse Repetition Frequency

The minimum pulse repetition frequency that can be used (Nyquist sampling) samples the radar twice for each antenna length displacement. The azimuth over-sampling ratio, OSA, scales the Nyquist rate to determine the minimum pulse repetition frequency that will meett functional requirements.

$$f_{pr} = \frac{OSA \cdot 2 N_A V_S 1000}{L}$$

I76 Slant range to data reference

This is the range to the reference incidence angle that is linked to the basic specification set.

$$R_{ref} = \sqrt{R_e^2 + (R_e + H)^2 - 2R_e(R_e + H)Cos(\psi_{ref} - \sin^{-1}\left(\frac{R_e \sin(\psi_{ref})}{R_e + H}\right)})$$

I77 Real Aperture Area

The real aperture area is the area illuminated by a pulse of duration τ at one instant of time. The azimuth beam width is expressed in radians.

$$A_{RA} = 0.000001 \frac{c\tau}{2} 1000 R_{ref} \varphi_{A1}$$

I78 Noise Temperature

The noise temperature is the physical temperature of a passive circuit that would produce a noise power equivalent to that generated by the receiver.

$$T_N = T_e 10^{\frac{F_N}{10}} 10^{\frac{L_{feed}}{10}}$$

I79 Beam Shaping Feasible?

The elevation angle subtended by the swath is tested against the two-way elevation beam width. The result is reported to the user.

$$IF(\varphi_S > 1.5\varphi_{E1}, YES, NO)$$

I80 3 DB Swath Width

The ground (geoid) swath subtended by the half power 2-way beam width of the aperture-limited antenna pattern is D_3 km. This value is specified at the centre of the selected swath as computed in N78.

$$D_3 = R_{ref}\varphi_E Cos(\psi_S)$$

I81 Minimum peak power (beam centre)

This is the transmitted power required if only the beam centre needed to meet the noise-equivalent cross section specification. Note that a SAR system uses its bandwidth coherently to achieve resolution and thus a single-pulse version of the radar equation is appropriate for this estimate.

$$P_{bc} = \frac{(4\pi)^3(1000R_{ref})^4 10^{\frac{L_{feed}}{10}} kT_N B10^5}{G^2 10^{\frac{\sigma_{NE}^0}{10}} \lambda^2 A_{RA} OSA \eta_A{}^2 OSR}$$

I82 Relative power at the swath edges

The relative swath edge power is estimated from the Sinc^2 functional model of the antenna pattern and the swath width. When the full aperture antenna beam closely matches the swath, this parameter is used to scale the beam centre power estimate to predict the required peak power. p_{rel} is imported from the Constants and Utilities worksheet.

I83 Adjusted peak power

The transmitted power at the beam centre, scaled by the swath edge relative power defines the minimum transmitter power (in Watts) needed to meet radiometric specifications. When the swath is not beam filling, a broadened beam estimate from the Selected Swath Calculations group fills this role. *Note that this is the signal power generated, not the power radiated.*

$$P_A = \frac{P_{bc}}{p_{rel}}$$

I84 Peak Transmitter Power

The peak transmitter power is estimated from the number of TR modules and the power generated by each module. It must be greater than the greatest minimum power estimate. P_T is used in all subsequent calculations. *Note that this is the signal power generated, not the power radiated.*

$$P_T = N_{TR}P_{TR}$$

I85 Transmitter power design Margin

The design margin is the total budget for all uncertainties that affect the ability of the transmitter, antenna and receiver to meet the Radar's sensitivity specification. Early in the design phase this number should be relatively large. As the design proceeds through successive iterations, the uncertainties are minimized and the margin gives a measure of the allowed degradation of components over the lifetime of the system. A comparison between this parameter and the desired margin in the input parameter list provides an indication of desirable component specification limits later in the design process.

$$M_A = IF(p_{rel>0.2}, 10Log10\left(\frac{P_T}{P_A}\right), 10Log10\left(\frac{P_T}{P_{\min}}\right))$$

I86 Range distance to the first ambiguity

The first range ambiguity occurs when radar returns from the previous pulse arrive at the same time as the current pulse. These pulses are returned from targets displaced by an additional range distance that is determined by the radar pulse repetition frequency. The ambiguous returns are weakened by increased distance and by the skirts of the antenna pattern. The range ambiguity distance is the slant range from an image point to the first ambiguity in km.

$$d_A = 1000\frac{c}{2f_{PR}}$$

I87 First ambiguity slant range

The total slant range of the ambiguity is in km.

$$R_{A1} = R_{ref} + d_A$$

I88 First Ambiguity Earth Centre angle

The angle at the earth centre between the sub-satellite point and the first range ambiguity is a measure of the ambiguity offset from the satellite track.

$$\alpha_{A1} = Cos^{-1}\left(\frac{(R_e + H)^2 + R_e{}^2 - R_{A1}^2}{2R_e(R_e + H)}\right).$$

I89 Incidence angle at the first ambiguity

The incidence angle at the first ambiguity is used in conjunction with terrain slope and terrain scattering properties to determine the strength of the ambiguous signals.

$$\psi_{A1} = Cos^{-1}\left(\frac{(R_e + H)^2 - R_e^2 - R_{A1}^2}{2R_eR_{A1}}\right)$$

I90 First Ambiguity angle from boresight

The antenna gain at the first ambiguity is determined by its angle from the antenna beam boresight.

$$\beta_{A1} = \psi_{A1} - \alpha_{A1} - \beta_E$$

I91 Relative power returned from the first ambiguity

The radar return power from the first ambiguity, measured relative to the peak return from the area of interest is determined by the antenna pattern and by the relative ranges. This calculation is only valid when the swath fills the aperture-limited antenna beam.

$$p_{A1} = Sinc^2(\frac{\beta_{A1}}{\varphi_E})\left(\frac{R_{ref}}{R_{A1}}\right)^2$$

I92 Relative range ambiguity

This is the relative ambiguity power in dB

$$A_1 = 10Log10(p_{A1})$$

3.4.2.2 Selected Swath Calculations

Parameters computed in the Selected Swath Calculations ate listed in Table 16.

Table 16 Parameters calculated in the Selected Swath Calculations group.

Parameter	**Symbol**	**Units**	**Location**
Elevation beamwidth (2 way)	φ_{E2}	deg	N75
Range to swath center	R_S	km	N76
Earth centre angle to swath center	α_S	deg	N77
Incidence angle at swath center	ψ_S	deg	N78
Illumination angle at swath center	β_S	deg	N79
Antenna gain (2 way)	G_2		N80
Real aperture area	A_2	m^2	N81
Transmitter power for sigma$^0_{NE}$ specification	P_σ	W	N82
Transmitter power margin	M_S	dB	N83
Resulting sigma$^0_{NE}$	$\sigma^0_{NE\_S}$	dB	N84
Required receiving window (microseconds)	T_R	μs	N85
Number of pulses in flight	N_f		N86
Pulse repetition interval (microseconds)	t_P	μs	N87
Relative swath start arrival time (microseconds)	T_{RG}	μs	N88
Swath returns fit in PRI			M89
Summed range ambiguity, swath center	A_S	dB	N90
TR module duty cycle	F_{Dut}		N91

N75 2 way elevation beamwidth

The transmit-receive elevation beamwidth may be either aperture limited or swath limited. If the beamwidth is aperture limited choose this case, else choose the swat-limited case.

$$IF(\varphi_E > \varphi_S, \varphi_E, \varphi_S)$$

N76 Range to the swath centre

This is the range to the centre of the slant-range swath. This does not correspond to the centre of the ground swath.

$$R_S = R_{Sn} + \frac{D_{SR}}{2}$$

N77 Earth centre angle to swath centre

This is the angle at the earth centre between the sub-satellite point and the centre of the selected swath. The angle is calculated in radians and is expressed in degrees.

$$\alpha_S = \alpha_{Sn} + \frac{D_{SR}}{R_e}$$

N78 Incidence angle at the swath center

ψ_S is calculated at the center of the selected swath.

$$\psi_S = Cos^{-1}\left(\frac{(R_e + H)^2 - R_e^2 - R_S^2}{2R_e R_S} \right)$$

N79 Illumination angle from the swath centre

This is the angle from nadir to the swath centre as measured at the satellite. The illumination angle couples the antenna gain to radar power estimates.

$$\beta_S = \psi_S - \alpha_S$$

N80 2 way antenna gain

The product of the transmitter and receiver antenna gain is adjusted for the effective elevation beamwidth (aperture limited or swath limited).

$$G_S^2 = 10Log10(G^2\left(\frac{\varphi_E}{Max(\varphi_E, \varphi_S)} \right)^2)$$

N81 Real Aperture Area

The surface area illuminated in one instant of time is the area of the real aperture of the radar at the geoid. The one-way azimuth beamwidth is expressed in radians.

$$A_2 = \frac{0.000001c\tau}{2} R_S 1000\varphi_{E1}$$

N82 Transmitter power for σ^0_{NE} specification

The transmitter power required to meet the noise-equivalent radar cross-section specification at the selected swath is computed from the single pulse form of the radar equation. *Note that this is the signal power generated, not the power radiated.*

$$P_\sigma = \frac{2(4\pi)^3(1000R_S)^4 10^{\frac{L_{feed}}{10}} kT_N 1000000B}{10^{\frac{\sigma^0_{NE}}{10}} 10^{\frac{G^2}{10}} \lambda^2 A_S OSA \eta_A^2 OSR}$$

N83 Transmitter power margin

The transmitter power margin measures how well the transmitter power calculated previously meets the swath requirements. If the margin is negative the designer can: relax the specification, increase the power delivered by each TR module, increase the number of TR modules or some combination of the preceding trades.

$$M_S = 10Log10\left(\frac{P_T}{P_\sigma}\right)$$

N84 Resulting noise-equivalent radar cross section

If specification change is the choice, this is the required new specification (with no remaining margin if the specification is reduced). Specification reduction is the last resort.

$$\sigma^0_{NE\_S} = \sigma^0_{NE} + M_S$$

N85 Required receiving window

If the signals from the entire swath are to be captured, the receiver must accept data for at least this time (given here in microseconds).

$$T_S = \frac{2D_{SR}}{1000000c} + \tau$$

N86 Number of pulses in flight

The spacecraft radar imaging geometry is based on large distances. The result is that a number of pulses are in-flight, propagating from the radar to the ground and from the ground to the radar at any instant of time. Radar returns being received now are the response of the terrain to a pulse transmitted N_f pulse repetition intervals ago.

$$N_f = Floor\left(\frac{2f_{PR}R_S 1000}{c},1\right)$$

N87 Pulse repetition interval

The time between transmitted pulses is given in microseconds.

$$t_p = \frac{1000000}{f_{PR}}$$

N88 Relative swath start arrival time

The arrival time of the first return from the imaged swath measured from the start of the previous transmitter pulse is reported in microseconds.

$$T_{RG} = \frac{2R_{Sn}}{1000c} - N_f t_P$$

N89 Radar Return timing evaluation

For the radar to work properly, the swath-start specifications and the pulse repetition frequency must be adjusted so that the radar returns from the terrain do not arrive while the radar is transmitting. A similar constraint can be added to isolate the desired swath from nadir returns. This condition has not been applied here. Transmit/receive pulse contention is reported to the user as a message but is not used in calculation.

$$\begin{aligned}&IF(T_{RG} > \tau + AND(T_{RG} + T_S < t_P), Swath\_returns\_fit\_in\_PRI,\\&Swath\_returns\_overlap\_Tx\_pulse)\end{aligned}$$

N90 Summed Range Ambiguity (Swath Centre)

Ambiguous range data arrive in the swath from range intervals that are integer multiples of the range ambiguity distance. The first four of these are summed in the ‘Constants and Utilities work sheet. The received ambiguity power, ‘A_S’, (normalized to radar returns from unity radar cross section) is imported from ‘Const and Util’ O10.

N91 TR Module duty cycle

The transmit-receive module duty cycle is the fraction of the time that it is transmitting.

$$F_{Dut} = \tau f_{PR}$$

3.4.2.3 Data Handling Calculations

A first-order estimate of the data volume that needs to be accommodated by the Radar system can be calculated from a combination of inputs and results from the preceding sections. It is assumed that only simple data compression processing is done in the data stream and that encryption is part of the downlink subsystem.

The parameters computed in the Data Handling Calculations Group are listed in Table 17.

Table 17 Parameters computed in the Data Handling Calculations group.

Parameter	Symbol	Units	Location
Number of receiving channels	N_{Rec}		I97
RF Sampling rate	f_{sam}	MHz	I98
Burst data rate	f_{DB}	Mb/s	I99
Data volume/burst	N_B	Bits	I100
Data volume with 8:4 BAQ compression	N_{com}	Bits	I101
Data volume with Auxiliary block	N_{ax}	Bits	I102
Average data rate with compression	f_{av}	Mb/s	I103
Data recorder capacity required	N_{rdr}	Bits	I104
Data recorder with no compression	N_{RDR}	Bits	I105

I97 Number of receiving channels

The minimum number of channels for MTI or polarimetric SAR applications is estimated from the maximum of the number of apertures and the number of polarizations.

$$N_{rec} = Max(N_A, N_P)$$

I98 RF sampling rate

The complex data-sampling rate is the signal bandwidth multiplied by the range over-sampling ratio. The assumed output is one complex pair of digitized samples (in parallel).

$$f_{sam} = B \cdot OSR$$

I99 Burst data rate

The radar system digitizers sample at rate f_{sam} and output 2Q bits per sample. The rate calculated here assumes a serial bit stream.

$$f_{DB} = 2 f_{sam} Q$$

I100 Data volume/burst

The size of the captured data block per radar pulse is determined by the swath width, resolution and quantization plus a sample set that corresponds to the length of the range chirp.

$$N_B = 2Q(N_s + \tau f_{sam})$$

I101 Data volume with 2:1 BAQ compression

Block Adaptive Quantization can be used with SAR data to provide minimum-loss data compression provided that compression ratio is not larger than 2. Studies have shown that this approach is more forgiving than coupling a small (16 to 32 level) quantization with automatic gain control to acquire the required raw-data dynamic range.

$$N_{com} = \frac{N_B}{2}$$

I102 Data volume per pulse with auxiliary data block

The data transmitted to the ground from the SAR contains both the quantized radar signal and an auxiliary data block that packages radar settings and spacecraft attitude information.

$$N_{Ax} = N_{com} + A_x$$

I103 Average data rate with compression

The radar captures the radar returns at the burst data rate but the data is buffered for formatting and is sent to the recording system at a continuous (average) data rate.

$$f_{av} = N_{Ax} f_{pr}$$

I104 Recorder capacity with compression

The data recorder needs to store the expected data for a specified number of minutes/orbit.

$$N_{rdr} = f_{av} T_{rec} 60$$

I105 The recorder capacity with no data compression

If no data compression is used, the recorder capacity is the total data volume over the recording window.

$$N_{RDR} = (N_B + A_x) f_{pr} T_{rec} 60$$

3.4.2.4 Downlink

The downlink group infers the effective data rate and the message time dilation factor for transmitting the radar data to a ground station. The calculated parameters are listed in Table 18.

Table 18 Parameters computed in the Downlink group.

Parameter	**Symbol**	**Units**	**Location**
Effective channel capacity	C_{cap}	Mb/s	N96
Time dilation factor for downlink	F_{cD}		N97
Time dilation factor with no compression	F_{ND}		N98

N96 Effective channel capacity

The effective channel capacity is the raw downlink capacity scaled by the encryption overhead. Encryption is assumed to be installed in the path from the recorder to the down-link transmitter.

$$C_{cap} = \frac{C_{ap} N_c}{1 + \frac{E}{100}}$$

N97 Time dilation factor for downlink

Time dilation factors greater than 1 indicate that data must be down-linked slower than real time.

$$F_{cD} = \frac{f_{av}}{1000000 C_{ap}}$$

N98 Time dilation factor with no compression

When the data is not compressed, the time dilation factor increases.

$$F_{ND} = \frac{2 f_{av}}{1000000 C_{ap}}$$

3.4.2.5 Image Properties

The image properties calculation group compiles basic image parameters that can be deduced from the spreadsheet analysis.

Table 19 Parameters calculated in the Image Properties group.

Parameter	**Symbol**	**Units**	**Location**
Slant Range resolution	ρ_R	m	N101
Finest Azimuth resolution (Full aperture)	ρ_A	m	N102
Slant Range sample interval	δ	m	N103
Azimuth Sample interval	d_A	m	N104
Doppler centroid	f_{Dop}	Hz	N105
Range samples	N_{Rn}		N106
Image Skew	ε	deg	N107

N101 Slant range resolution

ρ_R is imported from the Computed Satellite Values group.

N102 Finest azimuth resolution

The finest possible azimuth resolution is one half of the antenna length.

$$\rho_A = \frac{L}{2}$$

N103 Slant range sample interval

δ is imported from the Computed Satellite Values group.

N104 Azimuth sample interval

This is computed in surface distance (m) from the satellite speed scaled to the earth surface and from the pulse repetition frequency.

$$d_A = \frac{R_e V_S}{f_{PR}(R_e + H)}$$

N105 Doppler centroid

The Doppler centroid is the residual frequency bias of the azimuth phase history. It is estimated as a function of range during SAR processing.

$$f_{Dop} = \frac{1000 V_{sub} \sin(\varepsilon)\sin(\psi_T) - v_e \sin(\psi_T)\sin(\gamma)}{\lambda}$$

N106 Range Samples

The number of range samples in the full resolution image is rounded down from the swath width to range sample ratio.

$$N_{Rn} = Floor(\frac{1000 D_{SR}}{\delta}, 1)$$

N107 Image skew

The image is skewed by the radar squint angle, ε_P.

3.5 Control sheet Active Array Power and Heat

The Active Array Power and Heat module provides first-order estimates of the array power requirements and the heat generated by the embedded electronics. The calculations assume that the radar is radiatively cooled through the signal-emitting surface and that the active face of the antenna has been treated to maximize thermal emissivity. The earth forms the “cold load” for heat transfer.

The antenna is assumed to be thermally isolated from direct solar heating.

3.5.1 Inputs

This module employs a user definition of the electronics functions that are distributed over the back of the antenna and accepts user-defined unit power requirements and efficiency estimates. The user also provides estimates of the thermal emissivity and the thermal conduction properties of the array. The input parameters are found in the User Inputs and the Inputs and Estimates groups.

The input parameters for the Array Power and Heat module are listed in Table 20.

Table 20 Input parameters for the Array Power and Heat Module

Parameter	**Type**	**Symbol**	**Units**	**Cells**
TR power amplifier efficiency	User Input	η_{TR}		E112
TR receiver and control	User Input	P_{T1}	W	E113
Controllers/TR column	User Input	N_{T1}		E114
Controller power requirements	User Input	P_{con}	W	E115
Power conditioning efficiency	User Input	η_{pc}		E116
Array thermal emissivity	User Input	e_A	$W/m^2/K^4$	E117
Mean earth temperature	User Input	T_e	K	I112
Array thermal conductivity	User Input	k_A		I113

The first two entries in Table 20 define the power usage of the transmit-receive modules. In these devices, the transmitter circuit is only active during the transmitted pulse and the receiver and control circuitry is turned on for the duration of the data collection. The TR module controller manages power, internal switching and monitoring, transmit and receive path phase and receive path gain. Active array architectures for large antennas use distributed, local control to minimize signal propagation delay effects. This spreadsheet assumes that the array controllers are organized by active-array TR column. The number of controllers per column will depend on the redundancy strategy of the design. The array controllers have computation capability and local memory. Their functions are: to define the radar beam for each mode by controlling the associated TR modules, to monitor distributed environment sensors and to execute local test and calibration functions. The power management and power conditioning in large array antennas are also distributed functions containing many parallel units. This spreadsheet model does not assume an architecture but assigns an efficiency factor to the process. The Array Power and Heat module assumes that the bulk of the signal generation and receiving system resides in the satellite bus. If other architectures are used, this module must be modified.

3.5.2 Parameters Calculated in the Array Power and Heat Module

Table 21 lists the parameters calculated in the Array Power and Heat module.

Table 21 Parameters calculated in the Array Power and Heat module.

Parameter	Symbol	Units	Location
TR power requirements	P_{AT}	W	I114
Controller power requirements	P_{Cnt}	W	I115
Power conditioner requirements	P_{cd}	W	I116
Array power requirements	P_{Ant}	W	I117
RF loss	$P_{R\ loss}$	W	N112
TR power dissipation	$P_{TR\ dis}$	W	N113
Total dissipated power	P_{dis}	W	N114
Array power dissipated/unit area	P_{dens}	W	N115
Array temperature, radiation cooling	Λ_{AR}	K	N116
Electronics temperature	Λ	K	N117

I114 Transmit Receive module power requirements

The TR module receiver and control circuits are always active when the radar is collecting data but the power amplifier circuit is only activated when a pulse is being transmitted.

$$P_{AT} = N_T (P_{T1} + \frac{P_{TR} F_{Dut}}{\eta_{TR}})$$

I115 Controller power requirements

In this model the controller has been represented by a single power requirement estimate and no attempt has been made to relate the controller power consumption to the tasks being performed. The number of controllers is dependent on the number of TR columns under the assumptions of this model.

$$P_{Cnt} = \frac{N_T N_{T1} P_{con}}{N_E (1 - S_P)/2 + N_R (1 + S_P)/2}$$

I116 Power conditioner requirements

The power conditioner power consumption is estimated from the efficiency of the power conditioner system.

$$P_{PC} = (P_{AT} + P_{Cnt})(1 - \eta_{PC})$$

I117 Array Power Requirements

This is just the summed average power usage by the active components on the array.

$$P_{Ant} = P_{AT} + P_{Cnt} + P_{PC}$$

N112 RF loss

The array and its passive feeds absorb some of the transmitted signal power.

$$P_{R\_loss} = P_T(1 - \eta_A + (1 - 10^{-L_{Feed}/10}))F_{Dut}$$

N113 Transmit-Receive module power dissipation

The background power usage of the TR modules is usually larger than the losses associated with transmitting a pulse. The power requirement for this module is the sum of the output power and the internal losses.

$$P_{TR\_dis} = N_T(P_{T1} + \left(\frac{P_{TR}}{\eta_{TR}} - P_{TR}\right)F_{Dut})$$

N114 Total dissipated power

This is the total average power dissipated in the array.

$$P_{Dis} = P_{Cnt} + P_{CD} + P_{R\_loss} + P_{TR\_dis}$$

N115 Array power dissipated/unit area

The array power dissipation density provides a good measure of the cooling constraints. It is assumed that the power dissipation is distributed uniformly over the array.

$$P_{Dens} = \frac{P_{Dis}}{LW}$$

N116 Array temperature

The array is assumed to be passively cooled by thermal radiation from its active face. The earth forms the “cold load” of the cooling system. It is also assumed that there is no direct solar heating on the active face and that solar heat inputs through the rear thermal blanket is negligible (not a particularly good assumption). The radiation efficiency is determined by the thermal emissivity of the array. Although this parameter can be manipulated by treatment of the array face, the emissivity can be expected to change over the life of the satellite due to atomic oxygen interaction. Often beginning-of-life and end-of-life calculations are used to validate cooling assumptions.

$$\Lambda_{AR} = \left(\frac{P_{Dens}}{e_A}\right)^{0.25} + Te$$

N117 Electronics temperature

The array electronics resides on the back surface of the array and is cooled by conduction through the array layers. A mean thermal conductivity is used to estimate the temperature of the electronic components.

$$\Lambda_{el} = \frac{\Lambda_{AR}}{k_A}$$

3.6 Constants and Utilities Sheet

The Constants and Utilities worksheet has two functions. It supports the calculation process by storing constants used in other calculations and it contains calculations whose intermediate results do not need to be reported to the user. There are no direct user inputs to this worksheet and all dynamic, working parameters are imported.

3.6.1 Constants

The contents of the Constants module is listed in Table 22

Table 22 Constants resident in the Constants and Utilities ('Const and Util') worksheet.

Constant	**Symbol**	**Units**	**Location**
Speed of light	C	m/s	C5
Boltzmans constant	K	W/Hz/K	C6
Polar earth radius	R_P	km	C7
Equatorial earth radius	R_{ee}	km	C8
Length of day	M	s	C9

3.6.2 Imported Parameters

The imported parameters used in the Constants and Utilities Worksheet are listed in Table 23. The selector switch parameters S_X in G10:G13 have corresponding control variables given by $(3-2S_X)$ in cells H10:H13.

Table 23 Parameters imported into the Constants and Utilities worksheet

Parameter	**Source**	**Symbol**	**Units**	**Cell**
Target latitude	Control sheet E27	θ_T	Deg	G5
Satellite altitude	Control sheet E10	H	Km	G6
Maximum orbit latitude	Control sheet I14	θ_{Max}	Deg	G7
Orbit inclination	Control sheet E12	I	Deg	G8
Reference incidence angle	Control sheet E13	ψ_{Ref}	Deg	G9
Squint indicator	Control sheet C14	S_S		G10
Look direction indicator	Control sheet C34	S_L		G11
Latitude indicator	Control sheet C29	S_H		G12
Longitude indicator	Control sheet C32	S_E		G13
Target earth centre angle	Control sheet N31	α	Deg	G14
Antenna beamwidth (1 way)	Control sheet I61	φ_{E1}	Deg	G15
First ambiguity angle from boresight	Control sheet I90	β_{A1}	Deg	G16
Swath centre range	Control sheet N71	R_S	Km	G17
Ambiguity range offset	Control sheet I86	d_A	Km	G18
Boresight angle	Control sheet I64	β_E	Deg	G19
Orbits per day	Control sheet I13	N_O		G20
Orbit repeat cycle	Control sheet E21	T_D	Days	G21

The parameters that are calculated in the "Constants and Utilities" worksheet that are exported to the Control worksheet are listed in Table 24.

Table 24 Parameters calculated in the "Constants and Utilities" worksheet and exported to the "Control" worksheet. The destination column defines the destination cells in the "Control" worksheet.

Parameter	***Symbol***	***Units***	***Location***	***Destination***
Satellite speed	V_S	km/s	C15	I10, N104
Earth radius	R_e	km	C14	I11, N28
Average earth radius	$<R_e>$	km	C18	I12, I22
Average satellite speed	$<V_S>$	km/s	C19	I12
Equatorial squint angle	ε_e	deg	C20	I17, I27
New orbit period	T_{New}	min	G46	I21
Speed of light	C	m/s	C5	*I43, I55, I56, I77, I86, N81, N85, N86, N88*
Length of day	M	s.	C9	*N29*
First quadrant beam angle	γ_1	deg.	D49	*I28*
First quadrant latitude offset	θ_1	deg	D50	*I29*
First quadrant orbit centre angle	C_1	deg	D53	*I33*
Boltzman's constant	K	W/K/s	C6	*I81, N82*
Sinc^4			G32	*I82*
Sinc^2			G39	*I91*
Summed range ambiguity	P_{amb}		O10	*N90*

The local working variables in the "Constants and Utilities" worksheet are not tabulated but are defined in the text.

3.6.3 Functions group

C14 Earth Radius

The earth radius at latitude θ is calculated using a GEM6 (Goddard Ellipsoid Model 6) model of an ellipsoidal earth.

$$R_e = R_{ee} \sqrt{\frac{Cos^2(\theta_T) + \left(\frac{R_p}{R_{ee}}\right)^4 Sin^2(\theta_T)}{Cos^2(\theta_T) + \left(\frac{R_p}{R_{ee}}\right)^2 Sin^2(\theta_T)}}$$

C15 Satellite Speed

For circular orbits, the satellite speed is a simple function of the satellite altitude.

$$V_S = \frac{631.34816}{\sqrt{R_e + H}}$$

C17 Minimum orbit earth radius

The minimum earth radius under the satellite position is determined by the maximum latitude.

$$R_{e\_\min} = R_{ee}\sqrt{\frac{Cos^2(\theta_{Max}) + \left(\frac{R_p}{R_{ee}}\right)^4 Sin^2(\theta_{Max})}{Cos^2(\theta_{Max}) + \left(\frac{R_p}{R_{ee}}\right)^2 Sin^2(\theta_{Max})}}$$

C18 The average earth radius under the satellite track

The RMS value of the earth radius under the satellite track is computed from minimum and equatorial earth radii.

$$< R_e >= \sqrt{\frac{R_{e\_\min}^2 + R_{ee}^2}{2}}$$

C19 Mean Satellite Speed

The mean satellite speed is computed from the RMS satellite altitude.

$$< V_S >= \frac{631.34816}{\sqrt{< R_e > + H}}$$

C20 Equatorial squint magnitude

To increase image formation through-put and to decrease the complexity of the SAR processor, The radar beam can be dynamically squinted in azimuth to partially null the earth rotation velocity contribution to the signal phase. The squint is largest at the equator and varies over the orbit as the cosine of the orbit central angle.

$$|\varepsilon_e| = Sin^{-1}(2\pi Sin\left(i\frac{(R_{ee}+H)^{1.5}}{631.34816M}\right))S_S$$

C21 Equatorial squint

When the switches that determine beam direction are set, the equatorial squint has the sign determined by the switch product.

$$\varepsilon_e = |\varepsilon_e| S_O S_L$$

C22 Orbit type

The orbit type switch takes the value 1 when the orbit inclination is greater than 90 degrees (retrograde orbit) and takes the value –1 when the inclination is less than 90 degrees (prograde orbit).

$$S_O = 2Ceiling\left(\frac{\theta_{Max}}{i}, 1 \right) - 3$$

3.6.4 Satellite position from target position iteration

This algorithm is an iterative solution to the spherical geometry problem of finding the normal intersection of a great-circle arc (from a known point) of known length and unknown orientation with a great circle arc of known inclination and unknown length.

The calculation starts with a crude estimate of the satellite latitude offset from a known terrain coordinate. The calculation sequence follows for four iterations.

C27 Lattitude offset 1

$$d\theta_1 = \theta_T \left(1 - \frac{\theta_{Max}}{\theta_{Max} + \alpha S_L S_O} \right)$$

C28 Satellite latitude estimate 1

The satellite latitude is now estimated from the target latitude and the offset.

$$\theta_{S1} = \theta_T - d\theta_1 S_L S_O$$

C29 Orbit central angle 1

The orbit central angle is estimated from the satellite latitude.

$$C_1 = Sin^{-1}\left(\frac{Sin(\theta_{S1})}{Sin(i)} \right)$$

C30 Satellite track angle 1

The satellite direction of travel is computed as a clockwise-measured angle from north.

$$\chi_1 = 360(1+S_O)/2 + Tan^{-1}\left(\frac{1}{Cos(C_1)Tan(i)}\right)$$

C31 Radar Beam angle 1

The radar beam is assumed to point normal to the satellite track.

$$\gamma_1 = 90S_L + \chi_1 - 180\left(\frac{1+S_L S_O}{2S_L}\right)$$

C32 Satellite offset from the target 2

The second estimate of the latitude offset between the satellite and the target point is now made using the known earth-centre angle between the target point and the satellite and using the previous beam angle estimate.

$$d\theta_2 = Sin^{-1}(Sin(\alpha)Sin(\gamma_1))$$

C33 Error estimate 1

The new offset is used to construct an error estimate for the previous calculations set.

$$\delta_1 = \theta_T - \theta_{S1} - d\theta_2 S_H S_O$$

C34 Satellite latitude estimate 2

The satellite latitude is now re-estimated from the previous estimate and the error term.

$$\theta_{S2} = \theta_{S1} + \delta_1$$

C35 to C40 repeat the algorithm contained in C29 to C 34

The calculation is iterated four times and terminates at cell C53 to generate the outputs: C5, $d\theta_5$, and γ_4.
These are imported into Observation Geometry module as C_1, θ_1, γ_1 (Table 24). The iteration converges rapidly for most initial conditions.

3.6.5 Sinc^4

Calculate the signal response of a uniformly weighted antenna aperture to a radar swath that squaredsubtends angle 2φ where φ is measured from the antenna boresight.

G30, H30 Import the angle of interest, φ

G31 Compute a scaling constant

The argument of Sinc^4 is scaled to the 3 dB width of Sinc^2.

$$F_3 = \frac{0.44295}{\varphi_{E1}}$$

G32 Evaluate the function

$$S^{(4)} = \left(\frac{Sin(\pi F_3 \varphi}{\pi F_3 \varphi} \right)^4$$

3.6.6 Sinc^2

Calculate the two-way signal response of a uniformly weighted antenna aperture to a radar signal at angle φ from boresight.

G36 Scale the half-power beam width to one side of boresight

$$\varphi_{E2} = \varphi_E / 2$$

G37 Generate the scaling factor

$$F_2 = \frac{0.44295}{\varphi_{E2}}$$

G38 Calculate the function

$$S^{(2)} = \left(\frac{Sin(\pi F_2 \varphi}{\pi F_2 \varphi} \right)^2$$

3.6.7 Desired Orbit Repeat Cycle

This sequence calculates a revised estimate of the orbit period when an orbit-repeat-cycle length (days between repeats) has been specified. The calculations have been designed to introduce the minimum change to the orbit period at the selected, nominal satellite altitude.

G43 Fractional orbit per day

The fractional part of the Orbits-per-day parameter form the Control sheet is extracted.

$$F_O = N_O - Floor(N_O, 1)$$

G44 Minimum-residual Numerator

To obtain a specified orbit repeat cycle, the fractional part of the Orbits-per-day parameter must be replaced by a rational fraction whose denominator is the number of days between repeats. The fraction numerator is selected to provide the closest approximation to the fractional part.

$$N_{Min} = IF(ABS(F_O - Ceiling(N_D F_O, 1)) < ABS(F_O - Floor(N_D F_O, 1)), Ceiling(N_D F_O, 1), Floor(N_D F_O, 1))$$

G45 New number of orbits per day

The number of orbits per day is computed from the original estimate and the rational fraction.

$$N_{New} = Floor(N_O, 1) + N_{Min} / N_O$$

G46 New Orbit Period

The new estimate of an orbit period that will support the desired repeat cycle is computed in minutes.

$$T_{New} = \frac{1440}{N_{New}}$$

3.6.8 Range Ambiguity Calculation

The range ambiguity calculation estimates contributions from the first 4 ambiguities. In the worksheet the calculation occupies the array of cells J5 to O10. The algorithm progresses horizontally and the calculations are repeated vertically for each ambiguity order.

J6 Ambiguity Order

a=1:4 from J6 to J9

K6 Ambiguity slant range

This is the swath centre slant range plus the ambiguity range interval multiplied by the ambiguity order.

$$R_{Am} = R_S + d_A$$

L6 Ambiguity earth centre angle

This earth centre angle is calculated between the sub-satellite point and the ambiguous range.

$$\alpha_A = Cos^{-1}\left(\frac{<R_e>^2 - R_{Am}^2 + (<R_e> + H)^2}{2(<R_e> + H)<R_e>}\right)$$

M6 Ambiguity incidence angle

The incidence angle of the ambiguous point is calculated from its slant range.

$$\psi_{Aa} = Cos^{-1}\left(\frac{(<R_e> + H)^2 - R_{Am}^2 - <R_e>^2}{2<R_e>R_{Am}}\right)$$

N6 Ambiguity beam angle

This is the angle between the ambiguous point and the antenna boresight measured at the antenna.

$$\beta_{Aa} = \psi_{Aa} - \alpha_A - \beta$$

O6 Ambiguity strength

This calculation assumes that the antenna pattern results from uniform illumination of an aperture. More sophisticated patterns are not addressed.

$$A_a = \left(\frac{Sin(\pi F_3 \beta_{Aa})}{\pi F_3 \beta_{Aa}}\right)^2 \left(\frac{R_S}{R_{Am}}\right)^2$$

O10 Total ambiguity power

Sum the contributions from all orders as found in O5 to O9.

$$A_{Tot} = \sum_{a=1}^{4} A_a$$

4. Tips For Using The Spreadsheet Models

The spreadsheet contains coupled models to compute observation geometry, antenna properties and radar properties of a space-based active-array SAR from a partial, functional description of the radar. The spreadsheet calculations have been designed to investigate point parameter sets. This version does not generate graphics to display the impact of a range of values.

As the spreadsheet calculations do not preserve the history of a sequence of tests it is very important that the user document critical assumptions at the outset and track these throughout the analysis. The model Control Sheet can be printed as a report on a single legal-size sheet of paper. When combined with the current assumptions list, the printed Control sheet forms a summary of the latest investigation.

4.1 Inputs and Assumptions

The typical, initial information set to be evaluated (or to be advanced to a system design level) contains a mixture of functional and system parameters that describe aspects of a desired radar. The set is usually incomplete, the members of the set usually have differing levels of significance (ranging from absolute requirements to wish-list elements) and, the information in the initial set may, or may not, be internally consistent.

The User Input sections of the spreadsheet tool capture key elements of the initial information set and allow these to be augmented by assumed and deduced values to complete the information set for more detailed evaluation. In addition, The User Input sections also contain a set of controls that allow orbits, target positions and swaths to be quickly examined as part of the radar assessment.

- It is **very important** to construct an <u>input parameter list</u> that contains a "Quality Assessment" and a "Design Implication" note beside each entry. This list may be revised several times during a radar assessment and each revision should be saved to allow the user to track the assessment process.

The "Quality Assessment " note should contain:

<u>For "source" parameters:</u>

- The origin of the data
- Is the parameter:
    - required,
    - nominal,
    - desired,
    - optional?
- How reliable is the input?
- Is the parameter part of a:
    - Functional requirement
    - System requirement
    - Detailed requirement

For deduced parameters

- Evidence used
- Evidence source
- Critical arguments

For assumed parameters:

- Heritage (Where did this come from?)
- Certainty
  - Is this a "point" value or is it selected from a range?
  - Is this a guess?
- Uniqueness: (Are other values documented from other sources?)
- Reliability

The "Design Implication" note is constructed after a series of investigations and should contain:

Criticality

- Design driver?
- Trade option?
- Nominal?

Sensitivity

- Can be varied over a range without major design impact
- Small changes can result in major changes in design

Any other assumption not covered above should be included as a note at the start or end of the list.

When entering parameters into the spreadsheet tool it is advisable for the user to employ text colour as a means of visually identifying the input parameter source and/or reliability.

4.2 Using the Spreadsheet Tool

4.2.1 Parameter Consistency Tests

The initial input parameters often contain inconsistencies and implicit assumptions about requirements priorities that are not evident in the initial data set. Typical consistency examples are satellite altitude and orbit repeat cycle and the relationships between slant range resolution, ground range resolution and bandwidth.

Different orbit repeat cycles require different satellite altitudes. The resolution in this case is to treat the satellite altitude parameter as nominal and to compute the closest altitude that yields the desired orbit repeat cycle. The Platform module allows both the satellite altitude and the orbit repeat cycle to be entered. The spreadsheet software treats the satellite altitude as a hard, global variable for other calculations. The Computed Values section of this module calculates the satellite altitude required to match the repeat cycle requirement. The calculated value is not linked elsewhere and its entry as the satellite altitude for other work is left to the user.

The radar resolution in slant-range or ground-range and the radar bandwidth are closely coupled parameters. In normal radar design the slant-range resolution is determined by the bandwidth and the weighting applied for sidelobe suppression. The ground-range resolution is the projection of the slant-range resolution onto an assumed earth surface at a specified incidence angle. In the spreadsheet software, the range-code weighting is assumed to be uniform and the slant-range resolution is defined by the bandwidth only. The ground range resolution is defined by a projection onto the reference geoid. The Observation Geometry module in the spreadsheet allows one of the slant-range resolution, ground-range resolution or bandwidth to be accepted as the resolution parameter. All three parameters are calculated and presented in the Computed Satellite Values group. Inconsistencies in the input parameter set can be easily identified.

The Platform and the Observation Geometry modules of the spreadsheet allow the user to investigate the relationships between swath position, incidence angle, target position, resolution, swath-width, and bandwidth. The impacts of choices made for the high-level functional specification of the radar will appear in various parameters throughout the spreadsheet. The calculated values can be used to search for inconsistencies in the source data and to identify source parameters that drive the design complexity. The user can then try to identify the probable hierarchy of specification precedence.

Similar investigations can be conducted on parameters in the other spreadsheet modules. Other consistency examples are:

- the relationship between boresight angle, elevation steering range, antenna width, spacing of independently controlled rows in elevation and number of elevation rows;
- the relationship between swath width, swath incidence angle range, pulse repetition frequency, quantization, and transmit-receive window overlap;
- the relationship between range resolution, swath width, pulse repetition frequency and downlink capacity;
- the relationship between resolution and sample spacing;
- the relationship between the TR module power, the number of panels, the number of TR modules the transmitter power and the noise-equivalent radar cross section.

Depending on the level of detail available at the start of the investigation, numerous other consistency tests can be conducted on the input data set.

4.2.2 Evaluate stated assumptions and search for implicit assumptions

The functional requirements that define a radar and details related to its implementation are based on interacting sets of assumptions. Some of these are explicitly stated and some are implicit in the stated choices. Two key questions that need to be answered are: “Do all specified parameters apply to all implied conditions all of the time?” and “Are some combinations not allowed for reasons that have not been considered in the initial definitions?” Further questions such as: “What are the application objectives to be met by the radar design?”, “Are reasonable technology assumptions being made?”, “What are the most critical design constraints?”, etc. will need to be raised and examined.

The spreadsheet tool can be used to examine the impact of assumption sets and to look for combinations where a small subset of requirements has a disproportionately large impact. The spreadsheet software makes the assumption that the parameters entered in the input blocks are minimum (must be met or exceeded) requirements and computes free radar system parameters on this basis. Those parameters that represent “best guesses” can be treated as “free” system parameters that can be manipulated by the analyst within valid ranges to determine reasonable boundaries for the proposed design or to raise significant questions about the assumptions contained in the input specification set.

For example, if the specified ground range resolution is a hard requirement for all radar modes, then the computed bandwidth will be driven by the highest resolution and the smallest incidence angle in the radar coverage range. This will, in turn drive the required data volume and the required transmitter power. Relaxing this constraint for the steepest incidence angles may result in a major change in the number of transmit receive modules required. This raises the question of the importance of the constraint at the steepest angles and finest resolution. Depending on the selected radar frequency, the largest bandwidth may exceed international agreements on bandwidth control and, thus not be allowed. The assumption of ground range resolution as a critical parameter could be amended by the clause “when the required bandwidth is less than Y MHz.”

As a second example, radar specifications require a sensitivity measure. This is often expressed as a “noise-equivalent radar cross section”. How this specification is to be applied to the set of radar modes is often weakly defined.

- Does it apply to a single range and incidence angle?
- Does it apply to the beam centre for all modes?
- Does it apply to the swath edges?

The spreadsheet allows the “single point” and the swath edge definitions to be used directly to calculate the required active array. The swath centre definition can be examined by looking at the “minimum peak power” and the “relative power at the swath edge” entries in the spreadsheet. A “most probable” assumption can then be assigned, given some understanding of the design application of the radar system. The spreadsheet controls allow the user to fix the number of TR modules and then to explore the implications of the assumption made.

Questions that can be examined by the spreadsheet calculations are those in which the assumptions contained or implicit in the specification set have an impact of the gross (system level) definition of the instrument.

4.2.3 Available trade-offs and unanticipated functions

A large number of the spreadsheet inputs add instrument properties to the basic functional requirements for the radar. These usually have a heritage based on previous, broadly similar systems. They also have technological roots that may have grown somewhat since the technology was last employed in a space system. When these “free” parameters are manipulated within the bounds of available technology a number of options may appear that will provide alternative ways of meeting the specified requirements or that may allow “minimum cost” additional capabilities.

For instance, the relative cost of adding rows of active elements across the antenna width will increase the maximum incidence angle before grating lobes are excited. Does the operational advantages provided warrant the cost? The spreadsheet allows the number of rows to be input directly, allows the maximum incidence angle to be input directly and calculates the minimum number of rows required to meeting the grating lobe onset criterion. By setting a desirable maximum angle and adjusting the number of specified rows the correspondence between the minimum number of rows calculated and the number of rows added indicates the array requirement and allows an evaluation of the relative cost of this design modification.

Is the use of a larger number of lower-power, less expensive TR modules or a smaller number of higher power, more expensive TR modules a more reasonable choice? The impact of changing TR module power on the array architecture can be easily examined. As a side benefit, decreasing the number of azimuth radiators/TR module may allow electronic steering to be used to point the radar beam to zero Doppler without slewing the satellite in azimuth as it traverses its orbit. The zero-Doppler pointing has a large impact on SAR processor complexity and speed. If provided by electronic steering there may be a desirable cost offset. Where unsquinted operation was initially planned, an additional capability may be added at reasonable cost provided that the azimuth steering angle is greater than the required equatorial squint.

Given ground processor constraints, are there best choices for resolution vs swath width combinations? The primary indicator for this investigation is the number of slant-range samples and the adjustable parameters are range resolution, swath width, range over-sampling ratio and the chirp length.

In general, the spreadsheet provides a tool to perform first-order explorations of the relationships between functional requirements and radar design specifications. Simple design trade-offs may also be explored.

5. Annexes

5.1 Annex A The Excel Spreadsheet Model

The following hyperlink opens the spreadsheet model (contained on the accompanying floppy disk) for use. The software has been developed on Excel 2000 and Excel 97. It may not work well with older versions of the application.

A:\Array_R_1.xls

5.2 Annex B Variables Cross-reference Table

The table in this annex has been assembled form other tables in the report to provide a quick cross-reference between the spreadsheet model parameters and the report sections. The cell numbers are the spreadsheet locations of the parameter values.

“Control” worksheet				
Location	**Parameter**	**Symbol**	**Units**	**Cells**
Table 1 P 4	Satellite altitude	H	km	E10
	Terrain height	h	M	E11
	Orbit Inclination	i	deg	E12
	Reference incidence angle	ψ_R	deg	E13
	Squint selector	S_S		C14,E14
	Pass segment	S_N		C16,E16
	Satellite latitude	S_ξ	deg	C18,E18
	Hemisphere	S_H		C20,E20
	Desired orbit repeat cycle	N_D	days	E21
Table 3 P 6	Sub-satellite point speed	V_{sub}	km/s	I11
	Satellite period	T	min	I12
	Orbits per day	N_O		I13
	Maximum orbit latitude	θ_{Max}	deg	I14
	Orbit central angle	C_P	deg	I15
	Time from ascending node	t_P	min	I16
	Mechanical azimuth squint	ε_P	deg	I17
	Orbit type	S_O		H18,I18
	Longitude shift/orbit period	Δ	deg	I19
	Orbit track angle	χ_P	deg	I20
	New orbit period	T_{New}	min	I21
	Required satellite altitude	N_{New}	km	I22

Location	Parameter	Symbol	Units	Cells
Table 4 P10	Target latitude	θ_T	deg	E27
	Hemisphere (N/S)	S_H		C29,E29
	Target longitude	ξ_T	deg	E31
	Hemisphere (E/W)	S_E		C32,E32
	Look direction	S_L		C34.E34
	Pass segment	S_N		C35,E35
	Minimum incidence angle	ψ_{Min}	deg	E37
	Maximum incidence angle	ψ_{Max}	deg	E38
	Swath width	D	km	E39
	Range resolution	ρ_R	M	E40
	Range definition	S_ρ		C41,E41
	Target incidence angle	ψ_T	deg	C43.E43
	Swath near edge incidence	ψ_D	deg	C44,E44
	Range over-sampling ratio	OSR		E46
	Constrain bandwidth	S_B		C47,E47
	Bandwidth constraint	B	MHz	E49
Table 6 P 11	Beam squint	ε	deg	I27
	Target azimuth from satellite	γ	deg	I28
	Satellite latitude offset from target	θ_Δ	deg	I29
	Satellite longitude offset from target	ξ_Δ	deg	I30
	Satellite latitude	θ	deg	I31
	Satellite longitude	ξ	deg	I32
	Orbit central angle	C	deg	I33
	Orbit time from ascending node	T	min	I34
	Unwrapped longitude to ascending node	ξ_U	deg	I35
	Ascending node longitude	ξ_A	deg	I36
	Solar time from ascending node	T_{sol}	min	I37
	Satellite track angle	χ	deg	I38
	Previous track longitude at satellite latitude	ξ_{-1}	deg	I39
	Next track longitude at satellite latitude	ξ_{+1}	deg	I40
	Track separation at satellite latitude	D_{TR}	km	I41
	Slant range resolution	ρ_R	M	I43
	Bandwidth	B	MHz	I44
	Ground range resolution	ρ_G	M	I45
	Range sample interval	δ	M	I46
	Samples/slant range swath	N_S		I47

Location	Parameter	Symbol	Units	Cells
Table 7 P 15	Target visible to the radar			N27
	Local earth radius	R_e	km	N28
	Earth surface rotation speed	v_e	M/s	N29
	Target illumination angle	β_T	deg	N30
	Target earth centre angle	α	deg	N31
	Target offset from satellite track	d_T	km	N32
	Target slant range	R	km	N33
	Target illumination time	T_t	s	N34
Table 8 P17	Earth centre angle to far swath edge	α_f	deg	N37
	Earth centre angle to near swath edge	α_n	deg	N38
	Surface distance to access the far edge	d_f	km	N39
	Surface distance to access the near edge	d_n	km	N40
	Adjacent pass overlap (opposite look)	d_o	km	N41
	Access swath width	D_A	km	N42
	Range to near edge of far swath	R_f	km	N43
	Incidence angle, near edge, far swath	ψ_f	deg	N44
	Selected swath near edge offset angle	α_{Sn}	Deg	N45
	Selected swath near edge offset distance	d_{Sn}	Km	N46
	Selected swath near edge slant range	R_{Sn}	km	N47
	Selected swath ground range width	D_{SG}	km	N48
	Selected swath slant range width	D_{SR}	km	N49
	Selected swath far edge incidence angle	ψ_{Sf}	deg	N50
Table 9 P 20	Wavelength/frequency	S_W		C56,E56
	Wavelength/frequency	λ, f	m, MHz	E57
	Antenna length	L	m	E58
	Antenna width	W	m	E59
	Number of apertures	N_A		E60
	Number of polarizations	N_P		E61
	Number of panels	N_{pan}		E62
	Radiation efficiency	η_A		E63
	Feed loss	L_{feed}	dB	E64
	Boresight calculated/input	S_{Bor}		C65,E65
	Boresight angle	β_A	deg	E66
	Elev.row calc/input	S_{ER}		C67,E67
	Number of elevation rows	N_E		C68
	Array size calculations	S_P		C69,E69
	Input number of TR modules	N_{TR1}		E70

Location	**Parameter**	**Symbol**	**Units**	**Cells**
Table 11 P21	Wavelength	λ	m	I55
	Frequency	F	GHz	I56
	Maximum antenna gain (1 way)	G		I57
	Maximum antenna gain (1 way)	G_d	dB	I58
	Gain/aperture	G_{ap}		I59
	Azimuth beamwidth (1way)	φ_{A1}	deg	I60
	Elevation beamwidth (1way)	φ_{E1}	deg	I61
	Elevation beamwidth (2 way)	φ_E	deg	I62
	Beamwidth for swath coverage	φ_S	deg	I63
	Elevation boresight	β_E	deg	I64
	Elevation steering range	ϕ	deg	I65
	Fractional bandwidth	F_B		I66
	Antenna area	a_{Ant}	m^2	I67
Table 12 P 24	Elevation row spacing (wavelengths)	w_e		N55
	Number of rows in elevation	N_R		N56
	Minimum transmitter power	P_{Min}	W	N57
	Minimum number of TR modules	N_{TR}		N58
	TR modules/panel	N_{Tp}		N59
	Minimum number of azimuth radiators/panel	N_{Pa}		N60
	Radiators/TR	N_T		N61
	Radiator azimuth spacing (wavelengths)	w_a		N62
	Azimuth sub-array length	L_{sa}	m	N63
	Azimuth sub-array beam width	φ_{sa}	deg	N64
	Maximum electronic azimuth steering angle	ϕ_A	deg	N65
	Total number of radiators	N_{Rad}		N66
Table 13 P 28	Chirp length (micro-seconds)	τ		E75
	Noise equivalent sigma_0	σ^0_{NE}		E76
	Receiver noise figure	F_N	dB	E77
	Electronics temperature	T_e	K	E78
	Azimuth over-sampling ratio	OSA		E79
	TR power	P_{TR}	W	E80
	Range ambiguity	p_{Amb}	dB	E81
	Acceptable margin	Ma	dB	E82
	ADC quantization (I, Q)	Q	Bits	E83
	Auxiliary data block	A_x	Bits	E84
	Data recorder capacity	T_{rec}	Bits	E85
	Down-link channel capacity	C_{ap}	B/s	E86
	Number of down-link channels	N_C		E87
	Encryption overhead	E	%	E88

Location	Parameter	Symbol	Units	Cells
Table 15 P 29	Minimum pulse repetition frequency	f_{PR}	Hz	I75
	Slant range to data reference	R_{ref}	km	I76
	Real aperture area	A_{RA}	m^2	I77
	Noise temperature	T_N	K	I78
	Beam shaping feasible?			I79
	3 dB swath width	D_3	km	I80
	Minimum peak power (beam centre)	P_{bc}	W	I81
	Relative power at the swath edge	p_{rel}		I82
	Adjusted minimum peak power	P_A	W	I83
	Peak transmitter power	P_T	W	I84
	Transmitter power design margin	p_{marg}	dB	I85
	Range distance to first ambiguity	d_A	km	I86
	First ambiguity slant range	R_{A1}	km	I87
	Earth center angle at first ambiguity	α_{A1}	deg	I88
	Incidence angle at first ambiguity	ψ_{A1}	deg	I89
	First ambiguity angle from boresight	β_{A1}	deg	I90
	Relative received power from first amb.	p_{A1}		I91
	Relative range ambiguity (dB)	A1	dB	I92
Table 16 P 34	Elevation beamwidth (2 way)	φ_{E2}	deg	N75
	Range to swath center	R_S	km	N76
	Earth center angle to swath centre	α_S	deg	N77
	Incidence angle at swath centre	ψ_S	deg	N78
	Illumination angle at swath centre	β_S	deg	N79
	Antenna gain (2 way)	G_2		N80
	Real aperture area	A_2	m^2	N81
	Transmitter power for sigma$^0_{NE}$ specification	P_σ	W	N82
	Transmitter power margin	M_S	dB	N83
	Resulting sigma$^0_{NE}$	$\sigma^0_{NE\_S}$	dB	N84
	Required receiving window (microseconds)	T_R	µs	N85
Table 16 P 34	Number of pulses in flight	N_f		N86
	Pulse repetition interval (microseconds)	t_P	µs	N87
	Relative swath start time (microseconds)	T_{RG}	µs	N88
	Swath returns fit in PRI			M89
	Summed range ambiguity, swath center	A_S	dB	N90
	TR module duty cycle	F_{Dut}		N91
	Elevation beamwidth (2 way)	φ_{E2}	deg	N75

Location	**Parameter**	**Symbol**	**Units**	**Cells**
Table 17 P 38	Number of receiving channels	N_{Rec}		I97
	RF Sampling rate	f_{sam}	MHz	I98
	Burst data rate	f_{DB}	Mb/s	I99
	Data volume/burst	N_B	Bits	I100
	Data volume with 8:4 BAQ compression	N_{com}	Bits	I101
	Data volume with Auxiliary block	N_{ax}	Bits	I102
	Average data rate with compression	f_{av}	Mb/s	I103
	Data recorder capacity required	N_{rdr}	Bits	I104
	Data recorder with no compression	N_{RDR}	Bits	I105
Table 18 P 40	Effective channel capacity	C_{cap}	Mb/s	N96
	Time dilation factor for downlink	F_{cD}		N97
	Time dilation factor with no compression	F_{ND}		N98
Table 19 P 41	Slant Range resolution	ρ_R	m	N101
	Finest Azimuth resolution (Full aperture)	ρ_A	m	N102
	Slant Range sample interval	δ	m	N103
	Azimuth Sample interval	d_A	m	N104
	Doppler centroid	f_{Dop}	Hz	N105
	Range samples	N_{Rn}		N106
	Image Skew	ε	deg	N107
Table 20 P 42	TR power amplifier efficiency	η_{TR}		E112
	TR receiver and control	P_{T1}	W	E113
	Controllers/TR column	N_{T1}		E114
	Controller power requirements	P_{con}	W	E115
	Power conditioning efficiency	η_{pc}		E116
	Array thermal emissivity	e_A	$W/m^2/K^4$	E117
	Mean earth temperature	T_e	K	I112
	Array thermal conductivity	k_A		I113
Table 21 P 43	TR power requirements	P_{AT}	W	I114
	Controller power requirements	P_{Cnt}	W	I115
	Power conditioner requirements	P_{cd}	W	I116
	Array power requirements	P_{Ant}	W	I117
	RF loss	$P_{R\ loss}$	W	N112
	TR power dissipation	$P_{TR\ dis}$	W	N113
	Total dissipated power	P_{dis}	W	N114
	Array power dissipated/unit area	P_{dens}	W	N115
	Array temperature, radiation cooling	Λ_{AR}	K	N116
	Electronics temperature	Λ	K	N117

“Constants and Utilities” Worksheet

Location	Parameter	Symbol	Units	Cells
Table 22 P 46	Speed of light	c	m/s	C5
	Boltzmans constant	k	W/Hz/K	C6
	Polar earth radius	R_P	km	C7
	Equatorial earth radius	R_{ee}	km	C8
	Length of day	M	s	C9
Table 23 P 46	Target latitude	θ_T	deg	G5
	Satellite altitude	H	km	G6
	Maximum orbit latitude	θ_{Max}	deg	G7
	Orbit inclination	i	deg	G8
	Reference incidence angle	ψ_{Ref}	deg	G9
	Squint indicator	S_S		G10
	Look direction indicator	S_L		G11
	Latitude indicator	S_H		G12
	Longitude indicator	S_E		G13
	Target earth centre angle	α	deg	G14
	Antenna beamwidth (1 way)	φ_{E1}	deg	G15
	First ambiguity angle from boresight	β_{A1}	deg	G16
	Swath centre range	R_S	km	G17
	Ambiguity range offset	d_A	km	G18
	Boresight angle	β_E	deg	G19
	Orbits per day	N_O		G20
	Orbit repeat cycle	T_D	days	G21
Table 24 P 46	Satellite speed	V_S	km/s	C15
	Earth radius	R_e	km	C14
	Average earth radius	$<R_e>$	km	C18
	Average satellite speed	$<V_S>$	km/s	C19
	Equatorial squint angle	ε_e	deg	C20
	New orbit period	T_{New}	min	G46
	Speed of light	c	m/s	C5
	Length of day	M	s.	C9
	First quadrant beam angle	γ_1	deg.	D49
	First quadrant latitude offset	θ_1	deg	D50
	First quadrant orbit centre angle	C_1	deg	D53
	Boltzman’s constant	K	W/K/s	C6
	Sinc^4			G32
	Sinc^2			G39
	Summed range ambiguity	P_{amb}		O10

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The initial steps taken by a radar designer to evaluate new design concepts or to review designs from outside sources involve iterative use of first-order analysis algorithms to couple high-level functional descriptions of the radar to viable system specifications. These analyses provide the foundations for detailed design studies or for detailed performance predictions. This report and its companion Excel spreadsheet provide a first-order analysis package for the current generation of active-array space-based SAR systems. The analysis package covers aspects of orbit parameter selection, observation geometry, active array design, image properties and data handling and data link requirements. Analysis procedures that use multiple, systematic, model trials are discussed

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Space-based Synthetic Aperture Radar
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