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OCEAN WIND FIELD MEASUREMENT PERFORMANCE OF THE ERS-1 SCATTEROMETER

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ABSTRACT

In 1988, Europe will launch the next generation of its Earth Resources Satellites, the ESA Remote Sensing Satellite (ERS-1). The Active Microwave Instrumentation (AMI), which will be implemented on the ERS-1, is a 5.3 GHz multipurpose radar for land surface imaging, ocean wave spectrum measurement and wind observations over oceans.

The imaging and wave measurements apply Synthetic Aperture Radar (SAR) techniques, while wind field detection is performed by the Scatterometer as part of the AMI.

At DORNIER SYSTEM, the Scatterometer system design has been developed and optimized with the aid of a Performance Simulator.

This paper is aimed at giving an overview about the

- ERS-1 Scatterometer system design
- Error budget
- Overall calibration concept.

1. INTRODUCTION

During the last decade, microwave Scatterometers have been shown to be sensitive to ocean surface wind speed and direction in various aircraft programs, the SKYLAB S-193 experiment and SEASAT.

At microwave frequencies, the ocean surface roughness, which is a function of actual wind condition, appears like a reflection grating. Thus, there is a functional dependence of the normalized radar cross section ($\sigma°$) and the wind speed.

Moreover, the radar cross section is anisotropic with respect to the angle between wind vector and incident radar beam. With the aid of several $\sigma°$-measurements of the same area from different measurement directions, the actual wind vector in terms of speed and direction can be determined, using a specific mathematical model, which defines the relation between the radar cross section and wind speed, wind direction as well as incidence angle and antenna polarization.

Hence, spaceborne ocean wind field detection requires a microwave Scatterometer with multiple beams. The number of antenna configurations, which can be imagined, is nearly unlimited, 2, 3, 4 etc. beams with any combination of beam squint angle. However, when transmit power and mechanical limitations of a satellite platform are considered, the options reduce.

Furthermore, σ°-measurements of an ocean patch, from which the wind vector shall be derived are perturbed due to system noise, instrument calibration errors, atmospheric attenuation etc. The problem of ambiguous solutions for the wind speed arises, which sets the minimum bound for required σ°-samples and hence the beam number.

In order to identify the optimum beam configuration with regard to wind vector measurement accuracy, extensive analysis was peformed by DORNIER SYSTEM GmbH in close cooperation with the European Space Agency (ESA) and the Max Planck Institute at Hamburg (Germany) which has led to a 3 beam configuration.

2. ERS-1 SCATTEROMETER SYSTEM DEFINITION

2.1 System Geometry and Measurement Sequence

The Scatterometer as part of the Active Microwave Instrumentation (Wind Mode operation) illuminates the sea surface sequentially for reflectivity measurements by RF pulses at a carrier frequency of 5.3 GHz from different direction by 3 antennas. The nominal look angles of the antennas are 45 fore and aft of broadside as well as broadside to the satellite velocity vector. The overall system geometry is shown in Fig. 2-1.

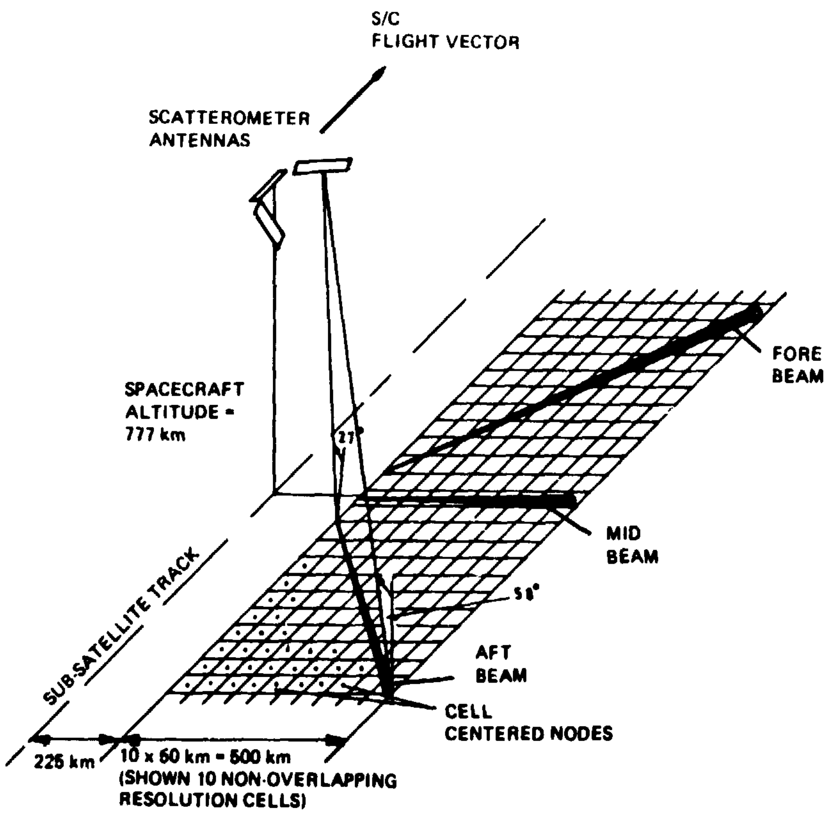

Fig. 2-1: Scatterometer Overall System Geometry

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Reflectivity data will be provided for a 500 km wide continuous swath along the satellite ground track to deduce wind speed and direction at nodes with 25 km separation along and across the Sub-Satellite track within the swath.

Each node is centered within a resolution cell of 50 x 50 km^2, which is determined in range direction by appropriate range gating of the received echo signal and in azimuth by averaging of corresponding range gated echo signals of 256 RF pulses.

In order to achieve a correct illumination of nodes by all three beams, the total satellite will be steered in yaw-axis (compensation of earth rotation effects) such, that the spectrum of the received echo of a RF pulse transmitted by the mid beam antenna will not be shifted in frequency (Doppler).

The yaw angle variation throughout the orbit related to the spacecraft velocity vector is sinusoidal with max. deflections at the equator ± 3.91° for a spacecraft altitude of 780 km.

2.2 Electrical Characteristics

The general processing flow of the AMI in Wind Mode operation (Scatterometer) is shown in Fig. 2-2.

A rectangular pulse at a carrier frequency of 123.4 MHz is generated, up-converted to 5.3 GHz and finally amplified to 4.8 kW peak transmit power before radiation via one of the three Scatterometer antennas. The pulselength will be different for the FWD/AFT-Beam and the Mid-Beam antenna and is determined by ground resolution requirements (50 km in range) and signal-to-noise ratio (SNR) optimization.

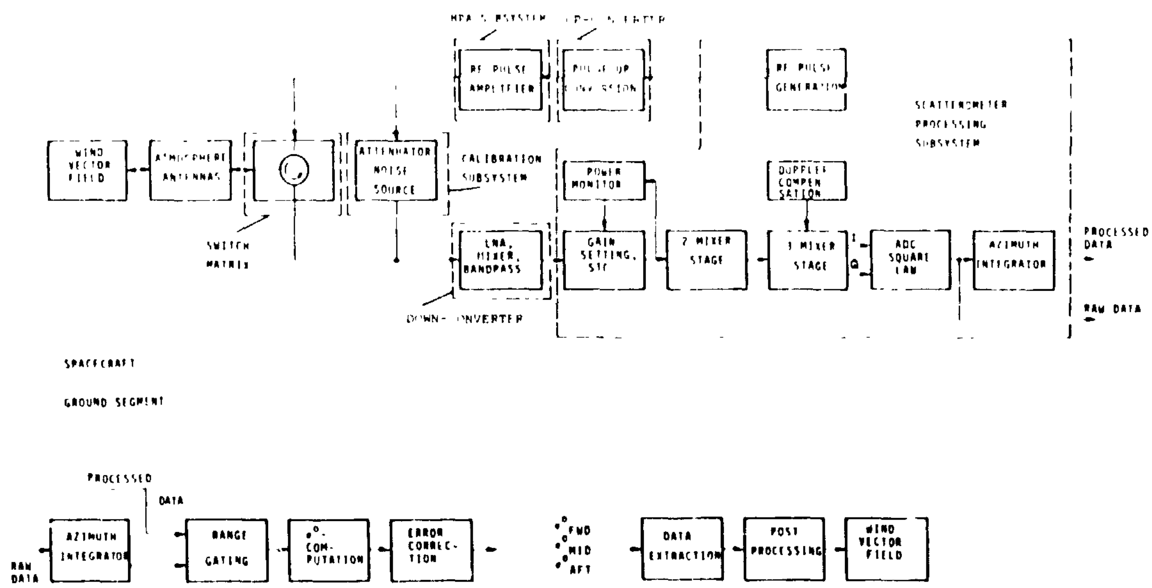

Fig. 2-3: Scatterometer Processing Flow

The received signal is amplified (LNA), down-converted and bandpass filtered. Within the next processing steps further down conversion to baseband including Doppler compensation for SNR maximization, low-pass filtering, A/D-conversion and quare-law detection is performed.

The samples of one echo signal are either transferred directly to ground (raw data transmission mode) or stored temporarily in a memory. Here they are summed up with corresponding samples to successive echos for averaging (data reduction) before transmission to ground.

As an internal calibration routine, the first RF pulse of the operational sequence of one antenna (32 shots) is routed back via the calibration unit (where it is delayed and attenuated) to the receiver to identify gain/loss variation within the transmitter/receiver processing chain.

Within the ground segment, gated integration of the averaged echo signal of 256 RF pulses is performed according to ground resolution requirements to extract the average signal power for a specific resolution cell (node).

Finally, the radar cross section ($\sigma°$) is derived from the received signal power value with the aid of appropriate conversion factors, which are determined by the nominal system transfer function as well as auxiliary data for error correction, provided by external and internal calibration routines.

Performing this for all beams, gives three $\sigma°$-values, which are passed to a data extraction algorithm for wind vector computation.

A summary of the main electrical system parameters of the ERS-1 Scatterometer is listed in Table 2-1.

2.3 Scatterometer Performance Evaluation

Two different error types contribute to the potential error in the measurement of the radar cross section $\sigma°$:

- bias errors (even and odd with regard to 3 Scatterometer antennas)
- random errors.

Both types limit the absolute radiometric resolution of the Scatterometer.

The ESA geophysical requirements for the Scatterometer in terms of wind field measurement accuracy are listed below:

- wind speed measurement range:
  4 m/sec < v < 24 m/sec*

- wind speed tolerance:
  ± 2 m/sec or ± 10 % whichever is larger

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- wind direction measurement range:
  $0^\circ < \phi < 360^\circ$*

- wind direction tolerance:
  $\pm 20^\circ$

*A priory probability of rank-1 solution of the data extraction algorithm (maximum likelihood estimator) being within the tolerance is 63 % (wind speed) and 55 %/75 % (wind direction) excl./including 180° ambiguity.

In order to fulfill the above geophysical requirements, the max. allowable errors in σ°-measurements amount to:

- even bias errors = ± 0.35 dB
- odd bias errors = ± 0.5 dB
- random errors = < 8.5 % (standard deviation)

The above data were established by ESTEC with the aid of detailed Monte Carlo Simulation taking into account an empirical C-band σ°-reference model. This C-band model, which forms the basis for the ERS-1 Scatterometer system design, has been developed by A.E. Long (1981), based on σ° data obtained with an airborne multifrequency coherent pulse radar by the Naval Research Laboratories and further analysis by Moore (1970) and Jones and Schroeder (1978).

In this formulation σ° is given by

$$\sigma^\circ = a \cdot v^c (1 + b_1 \cos \phi + b_2 \cos 2\phi)$$

where

v = windspeed
ϕ = wind direction
a, c, b_1, b_2 = given in an empirical form as a function of incidence angle

The random error in the σ°-measurement (Gaussian distribution is assumed) is determined by the normalized standard deviation (kp) of the received signal power, which is porportional to σ°.

It is calculated according to the formula

$$kp^2 = \frac{1}{B \cdot T_{SN}} \left[\left(1 + \frac{1}{SNR}\right)^2 + \left(\frac{1}{SNR}\right)^2 \cdot \frac{T_{SN}}{TN} \right]$$

and hence is a function of signal-to-noise ratio (SNR), system bandwidth (B) and the integration time of the signal + noise measurement (T_{SN}) and the noise only measurement (T_N).

The actual baseline of the system design concept leads to a normalized standard deviation of the received signal of < 9 % for worst case conditions (min. windspeed, crosswind).

Transmitter/Receiver:

o Transmit signal frequency:	5.3 GHz
o Transmit pulse length:	130 μsec (F,A)* 70 μsec (M)*
o Pulse repetition interval:	4.878 msec (F,A)* 4.347 msec (M)*
o Peak transmit power:	4 [illegible] kW
o RF average transmit power:	54 W
o Receive signal bandwidth (3 dB)	
- before Doppler compensation:	350 kHz
- after Doppler compensation:	9.2 kHz (F,A)* 17.3 kHz (M)*
o ADC-resolution:	8 bit (I,Q)
o Min. SNR:	0 dB

Antenna:

o Beamwidth (3 dB)	
- Azimuth	0.8°(F,A)*, 1.3°(M)*
- Elevation	26°(F,A)*, 24°(M)*

(shaped elevation gain pattern, figures represent swath coverage)

o Gain

(F,A)* : $> 31\text{ dB} - \frac{9\text{ dB}}{26^{\circ}}\Theta,\ 0^{\circ} < \Theta < 26^{\circ}$

(M)* : $> 29\text{ dB} - \frac{6\text{ dB}}{24^{\circ}}\Theta,\ 0^{\circ} < \Theta < 24^{\circ}$

Θ = antenna elevation angle

*(F,A) = fore and aft beam antenna
(M) = mid beam antenna

Table 2-1: Summary of Electrical Characteristics

Odd bias errors (relative beams) impact directly the measurement accuracy in terms of wind direction, while even bias errors degrade the windspeed measurement accuracy. The main error sources which contribute to the above error types, are listed below:

- Antenna elevation pattern
  - prelaunch gain measurement error
  - distortion during launch
  - in-flight thermal distortion
- Antenna pointing error
- Propagation path (atmospheric attenuation etc.)
- Transmitter/receiver gain fluctuations
- Stability of internal calibration subsystem.

Each of the above error souces which contribute to bias errors may be subdivided into static and harmonic portions. The latter are slowly varying errors of the order of an orbit in period (caused through thermal effects etc.).

Generally static errors may be corrected by appropriate instrument internal and external calibration which will roughly be discussed in the following chapter.

Harmonic errors appear twice within the system error budget, i.e. during external calibration and during nominal Scatterometer operation.

At the time this paper was established, the system error budget was under development and hence not yet ready for publication. It is believed that the requirement of an odd bias error of < 0.5 dB may be achieved, while an max. allowable even bias error of < 0.35 dB will cause problems. The minimization of the even bias error is subject of actual Scatterometer system design work. First results and a preliminary system error budget will be presented during the symposium.

2.4 Scatterometer Calibration

The Scatterometer requires a calibration strategy which provides absolute radiometric accuracy across the entire swath.

With regard to the radar equation* which is solved for $\sigma°$ (radar back-scattering coefficient) below, it becomes obvious, that absolute radiometric accuracy can only be achieved by a combination of external and internal (on-board) calibration methods.

$$\sigma° = (P_1 - P_2) \cdot \frac{(4\pi)^3 \cdot R^4}{\lambda^2} \cdot \frac{L_1}{v \cdot P_t} \cdot \frac{L_2}{G^2 \cdot A_{eff}}$$

(1) (2) (3) (4)

*$\sigma°$ calculation is an over simplification for clarity. In reality the illumination function must be taken into account

where

P_1 = Signal + Noise Measurement
P_2 = Noise measurement only
R = Slant range
λ = RF wave length
v = Receiver gain
P_t = Peak transmit power
L_1 = On-board loss (waveguide and circulator)
L_2 = Atmospheric attenuation
G = Antenna gain (one-way)
A_{eff} = Effective illumination field

(1) Signal + noise-measurement (P_1) and noise-only-measurement (P_2) are performed for noise subtraction
(2) System parameters to be calculated
(3) To be measured by internal calibration
(4) To be measured by external calibration

2.4.1 Internal Calibration

The so called "ratio method" is applied. The RF transmit pulse at the output of the HPA is delayed, attenuated and routed back to the receiver via the calibration subsystem (programmable attenuator etc.). This method will allow the compensation of non-linear effects of the transmitter/receiver transfer function.

2.4.2 External Calibration

The baseline involves two sets of measurements. The first is the relative cross swath calibration over the Brazilian Rain Forest and the second is absolute calibration at three points within an extended swath against ground transponders.

The relative cross-swath calibration is performed by taking two sets of measurements, one taken with the satellite stepped in the roll direction with respects to the other. Comparison of both measurements leads to the relative across swath system gain curve, which can be related to the absolute measurements against transponders.

3. CONCLUSIONS

The design phase of the ERS-1 Scatterometer is nearly finished. The overall system error budget taking into account hardware component stabilities is still under development. It is believed that the wind direction measurement accuracy may be achieved. The performance requirements for windspeed may cause problems due to an required absolute radiometric accuracy of 0.35 dB.

Actually a comprehensive System Simulator, which models the overall baseline ERS-1 Scatterometer system is under development at Dornier System. It will enable the Scatterometer equipment components to be specified in terms of required performance and the effects of any degradation investigated. This will allow the realistic prediction of the Scatterometer measurement performance.