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DESIGN OF BISTATIC ALTIMETRIC MISSION FOR OCEANOGRAPHIC APPLICATIONS

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Abstract—Ocean topography is mainly used for monitoring the ocean circulation and has been intensively studied through European and non-European missions in recent years starting from the Seasat mission and Geosat, ERS 1/2, Topex-Poseidon. In the near future, ENVISAT and Topex-Poseidon follow-on missions will continue the measurements.

In the framework of a study funded by the European Space Agency (ESA), the authors analysed the feasibility of using the innovative concepts of bistatic altimetry to improve the spatial sampling of topography measurements. This paper outlines the main results of this study by determining the primary altimeter design parameters. A simplified configuration, based on two free-flying satellites, has been assumed and either mono or multi-beam radar systems have been analysed and compared in terms of system complexity and requirements. © 1999 Lister Science.

INTRODUCTION

Ocean observation is essential to be able to understand the mechanical energy, mass and heat exchanges with the atmosphere and to improve our prediction capabilities of the world's climate at seasonal, interannual and even longer time scales.

Satellite sensors such as altimeters, scatterometers and radiometers are the only observing systems providing direct, continuous and quantitative measurements of the ocean surface on a global scale over long periods which are suitable for climate studies.

In particular, altimetry has come to be the central focus of mesoscale to global scale oceanography and polar ice sheet studies. It is of great interest since the precise and accurate measurement of sea surface shape and polar ice caps is the only physical variable, measurable from space, that is directly and simply connected to water large-scale movement, to ice sheet volume and to the total mass and volume of the ocean.

For this reason, in recent years, ocean topography has been extensively observed through several satellite altimetric missions (i.e. Seasat, Geosat, ERS1/2, Topex/Poseidon) and will continue to be studied with the Topex/Poseidon follow on and ENVISAT missions. In addition, topography has been identified as a candidate explorer for the 2000–2010 period at the 1996 Earth Observation User Consultation Meeting [1].

Ocean observations require quite short revisit times (10 days as a worst case for high latitudes circulation) and quite dense spatial sampling (30 km for ocean mesoscale) with coverage extended up to high latitudes except in the instance of global circulation.

Experience has shown that it is not possible to optimise one sampling of any single satellite mission to observe all oceanic processes and regions, while some advantages can be gained if more instruments are considered in a complementary way. For example, the fast varying tropics, large scale disturbances and western boundary currents are covered by ERS1/2 on a 35 day orbit whilst the mesoscale and high latitudes are observed by the Topex/Poseidon high inclination orbit (66°).

Therefore priorities in the field of climatological studies would have to be restated and addressed to a specific mission.

The general feeling is that the tropics are the main engine, and that they should be adequately sampled in order to get the first order level in models. It is likely that a higher repeat sampling rate with coarser track spacing would be recommended instead whilst still covering high latitudes up to the ice edge.

An attractive solution is offered by the innovative measurement concept of bistatic altimetry [2] that can enhance the spatial sampling with respect to figures achievable by a single satellite system and without recurring to complex constellations of monostatic pulse limited altimeters.

In the following, after a short review of the key concepts, the expected signal to noise ratio (SNR) of the bistatic echo is evaluated on the basis of a simplified geometry and antenna pattern.

By fixing an adequate level of SNR, an optimised parametric analysis is performed, aimed to determine the main system parameters: antenna pointing and aperture angles, transmitted peak power, pulse length and repetition frequency. Either the possibility of using mono and multi-beam systems is investigated and a final operative configuration chosen.

REVIEW OF KEY CONCEPTS

In a straightforward way, a bistatic radar system is defined when antennas for reception and transmission are physically separated. In this case, the location of the target (*T*) depends on the distance (*B*) between the transmitting (*S*1) and receiving antennas (*S*2), called baseline, and the measured propagation path. Targets for which the sum of distances from the transmitting and receiving antennas is constant, can not be resolved in distance by the bistatic system. These point targets identify, in the three-dimensional space, an ellipsoid, whose intersection with a generic plane determines ellipsoidal isorange contours.

Fig. 1 shows the isorange contours on a plane Γ, tangent to the Earth surface, due to two spaceborne radar altimeters at an altitude *h*. The tangent point for which the sum of the distances from the two satellites is minimal is called the *bistatic point* and it is characterised by a *bistatic angle* θ from the *S*1 nadir direction.

In the monostatic case, the isorange contours are circles and the area delimited by two consecutive ones is constant over the swath and it is given by:

$$\Delta S_{\mathrm{mo}} = \pi r h \tag{1}$$

where *r* is the radar resolution. The last property is also satisfied in the bistatic configuration, where the area delimited by two consecutive ellipses can be written as:

$$\Delta S_{\mathrm{bi}} \approx \frac{\pi h r}{\cos^2\theta} \tag{2}$$

These two area expressions affect the signal to noise ratio that, for a generic bistatic radar system, can be written as:

$$\mathrm{SNR} = P_{\mathrm{p}} \frac{G(S1,T)}{4\pi R_{\mathrm{T}}^2} \frac{G(S2,T)}{4\pi R_{\mathrm{R}}^2} \frac{\lambda}{4\pi} \sigma \frac{1}{kT_0 B_{\mathrm{n}} F} \frac{1}{L_{\mathrm{a}} L_{\mathrm{RF}}} \tag{3}$$

where P_{p} is the transmitted peak power, $G(x, y)$ is the general formulation of the pattern gain, R_{T}, R_{R} are the distances transmitter-target and target-receiver, λ is the wavelength, σ is the target radar cross section, kT_0B_nF is the noise power, with *k* being the Boltzman constant, *F* the receiver noise, T_0 the system noise temperature and B_{n} the system bandwidth, L_{a} is the total atmospheric loss, L_{RF} is the radio-frequency loss.

In the following analysis, only the peak value of the SNR will be considered as design parameter, i.e. the one produced by the nearest scattering area Σ_0 of Fig. 1.

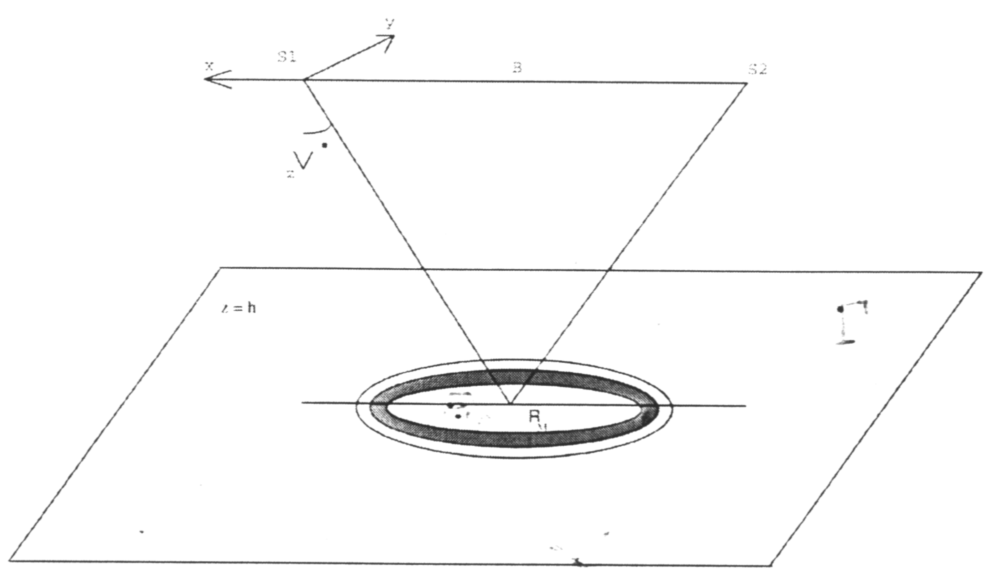

Fig. 1. Simplified bistatic geometry.

In the case of monostatic configuration, the SNR can be written as:

$$\mathrm{SNR_{mo}} \approx C\overline{\sigma^0}\frac{G_{\max}^2}{h^4}\Delta S_{\mathrm{mo}} \tag{4}$$

with:

$$C = \frac{P_{\mathrm{p}}\lambda^2}{(4\pi)^3 kT_0 B_n F L_{\mathrm{RF}} L_{\mathrm{a}}} \tag{5}$$

and where $\overline{\sigma^0}$ is the backscattering coefficient at nadir averaged over the integration area Σ_0. By considering the reference frame centred in $S1$ of Fig. 1, the analysis of the bistatic case is straightforward, since it is possible to write:

$$\mathrm{SNR_{bi}} \approx C\overline{\sigma^0_{\mathrm{eq}}}\frac{G(S1,T)G(S2.T)}{R_{\mathrm{T}}^2 R_{\mathrm{R}}^2}\Delta S_{\mathrm{bi}} \tag{6}$$

where an equivalent mean backscattering coefficient $\overline{\sigma^0_{\mathrm{eq}}}$ can be introduced by averaging over Σ_0 an equivalent backscattering coefficient which includes the mechanisms of bistatic scattering. Due to the small bistatic angles involved (<10°) and by considering gently undulating surfaces with large radius of curvature compared with the incidence wavelength in the Kirchhoff approximation [3], a very slight variation from the value used in the monostatic case is expected. Therefore, switching from monostatic to bistatic configuration, the changes in the expected SNR can be mainly associated with the different antenna pattern weight and the variation of the responding scattering area.

ORBITAL CONSIDERATIONS

The selection of a suitable orbit is out of the scope of the present work. The analysis of the bistatic altimeter system has been performed on the basis of the orbital parameters shown in Table 1, which have been determined to satisfy the main science requirements in terms of spatial and temporal sampling.

By fixing an orbiting right-handed reference frame in the satellite centre of mass (y axis perpendicular to the orbital plane and z axis along the local vertical towards Earth's centre) the variation of the baseline components along the orbit can be evaluated. Fig. 2 shows their behaviour starting from the equator (null anomaly) and does not include the satellites positions for which the baseline length is less than 30 km since the bistatic measurements are considered to be not significant.

The component along the y axis, the largest one, is due to the difference in the ascending node and,

Table 1. Main orbital parameters of the chosen bistatic constellation

Semi-major axis	7085.6996 km
Inclination (mean)	98.218390°
Eccentricity (mean)	0.00106689
Argument of perigee	90°
RAAN	270°
Mean Anomaly	90°
Revolutions in a cycle	131
Repetition cycle	9 day
Mean Motion (J2 corrected)	14.564 rev/day
Subcycle period	2 day
Revolution period	98.931327 min
RAAN rate	0.985599°/day
Perigee height	700.0000 km
Apogee height	715.1193 km
Equator cross separation	305.916 km
RAAN difference	0.916029°
Anomaly difference	0.1617°

as expected, it changes sign passing over the poles since the satellites switch their mutual position Table 1. The component along the x axis is due to the time lag introduced between the two satellites for safety reasons, while the z component is caused by the orbital geometry and it is surely negligible.

As a consequence, this strong variability of the baseline components along the orbit entails significant changes of the relative position of the bistatic point with respect the two satellites.

For further evaluation of SNR, it is preferable to express the position of the bistatic point by means of two angles measured in the elevation plane (yz) and in the azimuth plane (xz). Fig. 3 shows, for each satellite of the bistatic pair (dotted and solid line), those azimuth and elevation angles which can be viewed as the steering angles needed to align the antenna broadside with the line of sight of the bistatic point.

Of course, the most significant angle is the steering angle in the elevation plane since it is mainly caused by the variation of the y component of the baseline, while the other one is due to the variation of the x component.

As expected, due to the symmetric position of the bistatic point, the steering angles needed for one satellite are opposite to those required for the other one.

PEAK SIGNAL TO NOISE RATIO EXPRESSION

In evaluating the expected SNR peak value, the simplified geometry of Fig. 1 can be still considered if the S1 satellite is centred on an orbiting

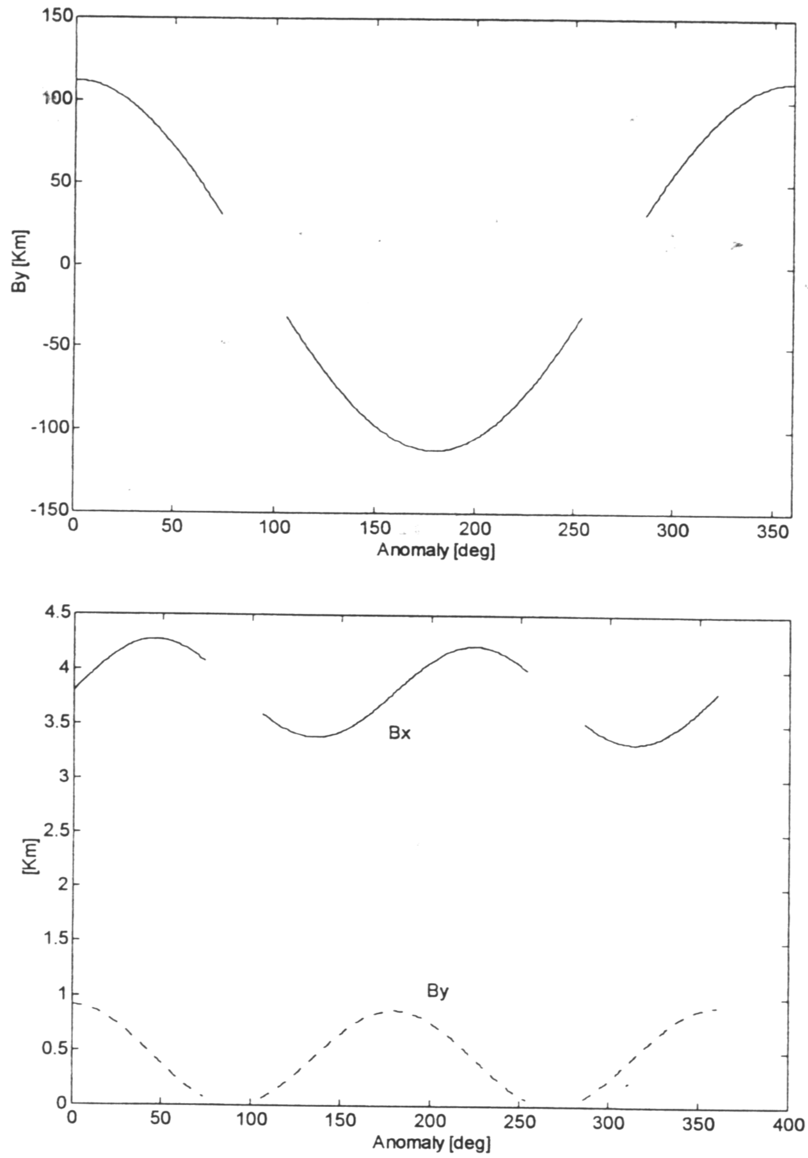

Fig. 2. Baseline components as a function of the anomaly along the orbit.

reference frame. The general formulation is that of Eq. (6) where the directions of the bistatic point (the target T) and the antenna pointing can be expressed with $(\vartheta_x, \vartheta_y)$ and $\overline{\vartheta_x}, \overline{\vartheta_y}$ respectively. As mentioned before, the first couple of angles depends on the variation of the baseline components along the orbit as:

$$\begin{cases} \vartheta_x = \tan^{-1}(B_x/2h) \\ \vartheta_y = \tan^{-1}(B_y/2h) \end{cases} \quad (7)$$

Therefore, by assuming small angles, the antenna gain in the direction of the bistatic point can be expressed as:

$$G(S1, T) = G_{\max} \exp\left[-\log 2 \frac{\tan^2(\vartheta_x - \overline{\vartheta_x})}{\tan^2(\vartheta_{3x}/2)}\right] \exp\left[-\log 2 \frac{\tan^2(\vartheta_y - \overline{\vartheta_y})}{\tan^2(\vartheta_{3y}/2)}\right] \quad (8)$$

The maximum antenna gain ($G_{\max}$)can be related to the –3 dB antenna apertures $(\vartheta_{3x}, \vartheta_{3y})$ as:

$$G_{\max} = \frac{4\pi}{\vartheta_{3x}\vartheta_{3y}} \eta_{\text{tot}} \quad (9)$$

where η_{tot} includes either the aperture and ohmic losses and the tapering efficiency.

By considering equal antennas on-board of the two satellites and by applying the symmetry of the configuration, the bistatic SNR becomes:

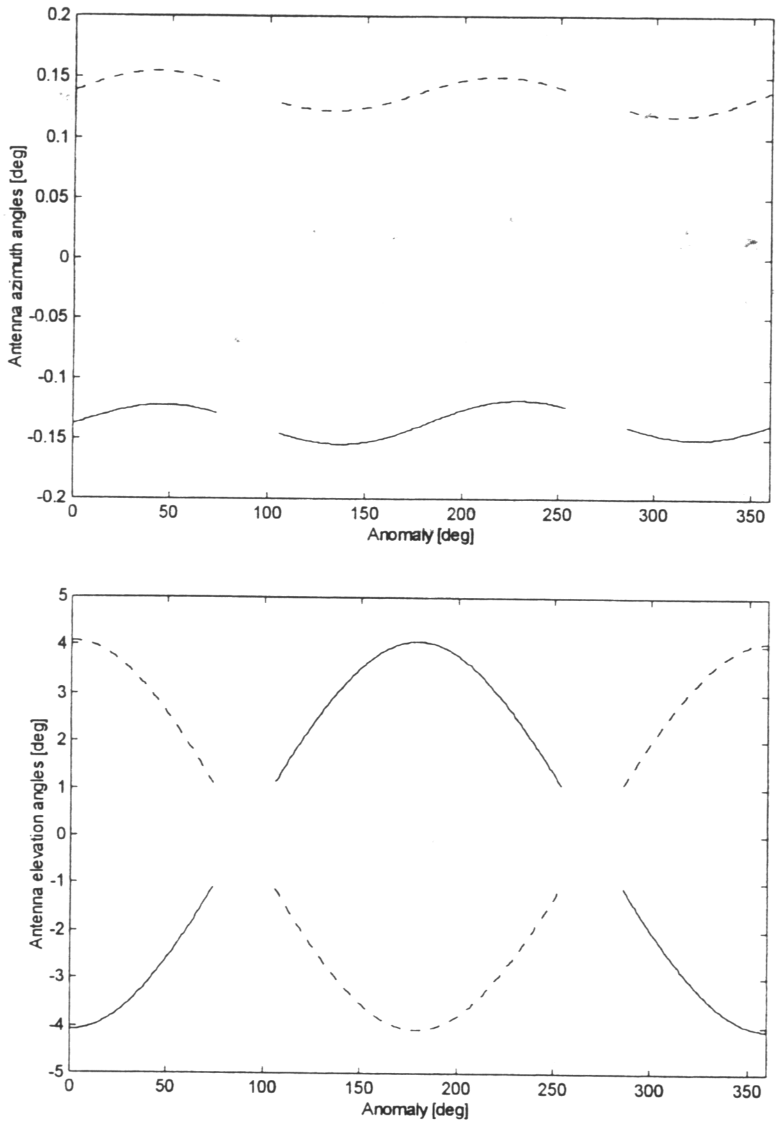

Fig. 3. Position of the bistatic point measured by means of the two antennas steering angles.

$$\mathrm{SNR_{bi}} = K_{\mathrm{SNR}} \frac{E}{\vartheta_{3x}^2 \vartheta_{3y}^2} \frac{1}{h(4h^2 + B^2)} \exp\left[-2\log 2 \frac{\tan^2(\vartheta_x - \overline{\vartheta_x})}{\tan^2(\vartheta_{3x}/2)}\right] \exp\left[-2\log 2 \frac{\tan^2(\vartheta_y - \overline{\vartheta_y})}{\tan^2(\vartheta_{3y}/2)}\right] \quad (10)$$

where $E = P_p \tau$ is the transmitted energy and

$$K_{\mathrm{SNR}} = \frac{r\lambda^2}{kT_0 F L_{\mathrm{RF}} L_a} \overline{\sigma_{\mathrm{eq}}^0} \eta_{\mathrm{tot}}^2 \quad (11)$$

SYSTEM DESIGN

The general goal consists in determining the main spaceborne altimeter system parameters, such as the transmitted peak power, the pulse length and repetition frequency, the antenna pointing and aperture angles.

On the basis of Eq. (10), once inverted, the peak transmitted energy can be expressed as a function of SNR through the other system parameters. In fact, for limiting the system power requirement, we assume a SNR level of 10 dB and thus determine the antenna characteristics which minimises the required energy along the orbit.

To this end, some general considerations can be done. Firstly the variation of the bistatic SNR along the orbit is mainly due to the corresponding variation of the baseline components that cause changes of the $(\vartheta_x, \vartheta_y)$ angles. Satellite altitude variations from the mean geoid are less significant, yet they can be easily evaluated and taken into account.

Therefore, keeping the other parameters unchanged, the peak-to-peak variations of the bistatic SNR can be decreased by pointing the antennas to minimise the variations of the tangent's arguments involved in Eq. (10).

For the determination of the optimal antenna apertures, the minimisation of the energy to be transmitted entails (regardless of the subscript x and y) the solution of the following equation:

$$1+\left(\frac{\vartheta_3}{2}\right)^2-\log2\tan^2(\vartheta-\overline{\vartheta})\frac{\vartheta_3}{\tan^2(\vartheta_3/2)}=0 \qquad (12)$$

which can be analytically solved, by considering small angles:

$$\frac{\vartheta_3}{2}=\left|\tan(\vartheta-\overline{\vartheta})\right|\sqrt{2\log2} \qquad (13)$$

Of course, if the SNR level threshold should be maintained along the whole orbit, the worst case of Eq. (13) should be considered, in correspondence with the maximum expected steering angle.

In the following, taking into account the previous considerations, three main operative options involving both single and multiple antenna systems have been studied.

Single-beam system

In this case we are interested in investigating the possibility of using a single nadir pointing and large beamwidth antenna ($\overline{\vartheta_x}=0, \overline{\vartheta_y}=0$) on-board of each satellite of the bistatic pair for acquiring mono and bistatic echoes simultaneously. From Eq. (10) it is obvious that for obtaining acceptable levels of SNR, the antenna pattern should be tailored to sufficiently cover the bistatic point for every baseline value during the orbit. This means dealing with large beamwidths which can justify some further approximation in the evaluation of SNR.

By neglecting the baseline components along the y and z axes and by evaluating the optimal value of the antenna aperture in the across-track direction (x axis) by solving Eq. (13), the following minimal energy has to be transmitted for assuring a value of 10 dB for the receiving bistatic SNR:

$$E_{\min}=\frac{20e\log2}{K_{\mathrm{SNR}}}(4h^2+B^2)\frac{\vartheta_{3y}^2B^2}{h} \qquad (14)$$

By using the values shown in Table 2, which can be considered quite typical for this kind of system, the minimal energy to be transmitted as a function of the along-track (y axis) antenna aperture and for various baseline values is shown in Fig. 4.

As expected, the required level of SNR can be maintained along the whole orbit (up to about 110 km of baseline) either by transmitting very high levels of energy or by using very large antenna in the along-track direction (x axis).

Table 3 shows some design examples where the antenna size has been evaluated by considering an uniform illumination.

To make a comparison, it can be useful to reminder that the RA-2 system, on-board of the ENVISAT platform, transmits an energy of 1 mJ per pulse by using a circular antenna one meter wide [4]. In a bistatic configuration, by using a similar antenna an energy fourteen times greater has to be transmitted (40 mJ) or, equivalently, a very wide antenna has to be used (5.56 m). These requirements can strongly compromise the system feasibility and can justify the efforts in investigating alternative option based on the use of multi-beam systems.

Table 2. Reference system parameters values

Satellite altitude	800 km
Wavelength	2.2 cm
Total antenna efficiency η_{tot}	0.5
Mean equivalent bakscattering coefficient $\overline{\sigma^0_{eq}}$	6 dB
Noise figure	4 dB
Radio-frequency losses	4 dB
Atmospheric losses	2 dB
Temperature	290 K
Radar resolution	0.9375 m

Table 3. System design examples with optimal value of the across track -3dB antenna aperture

Optimal antenna X aperture (°)	9.7			
Antenna Y aperture (°)	0.2	0.35	0.5	1
Transmitted energy (mJ)	2	5	10	40
Baseline km	115			
Antenna gain dB	39.2	36.7	35.2	32.2
Antenna size m X	0.11			
Y	5.56	3.18	2.22	1.11
SNR (dB)	10.7	9.8	9.7	9.7

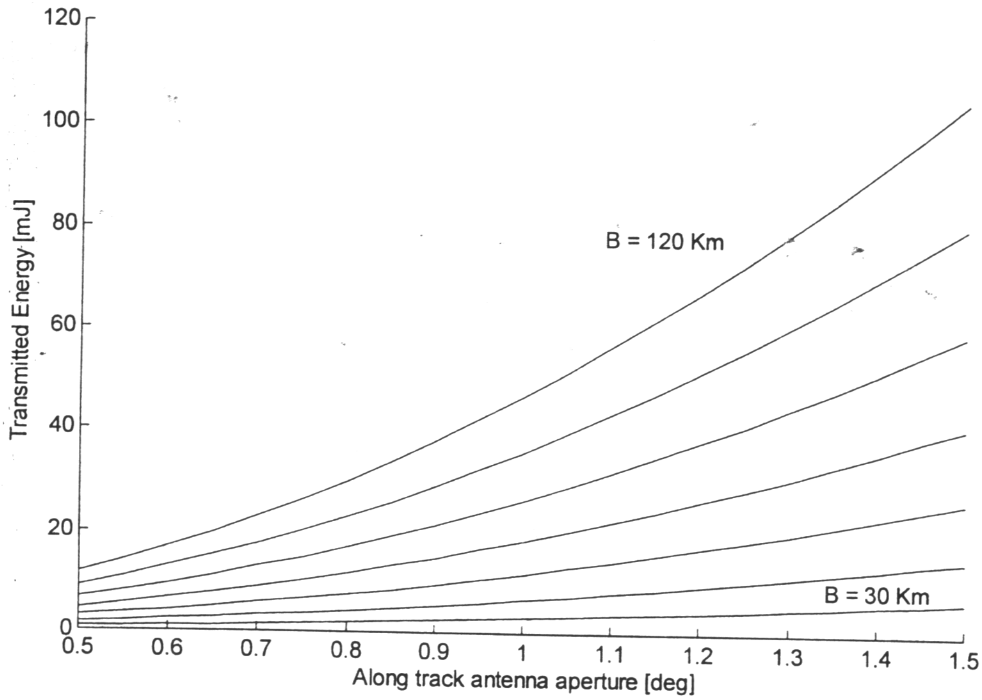

Fig. 4. Minimal values of transmitted energy which assures a signal to noise ratio of 10 dB as a function of the along track —3dB antenna aperture

Three beams system

The central beam shall be devoted only to the monostatic measurements and, therefore, shall be pointed along the nadir direction. The bistatic measurements shall be performed by the other two beams which shall be adjusted in order to compensate for the baseline variations.

Of course the bistatic beams should be offset to the right and left with respect to the the nadir direction and they have to be used alternatively on the ascending and descending part of the orbit, since the satellites of the constellation change their mutual when position passing over the poles. The optimal antenna pointing angles in the elevation and azimuth planes are shown in Table 4 and they have been determined as the mean between the maximum and the minimum values of the steering angles in the corresponding plane of Fig. 1.

The optimisation procedure of the antenna apertures entails a value in the elevation plane of 3.55° while, in the azimuth plane, an unfeasible value is attained. A value much greater than the optimal should therefore be selected.

If a RA-2 like value is considered (1.3°), the energy to be transmitted can be determined by using Eq. (10) and its variations along the orbit can be shown (shown in Fig. 5), analysis shows that a value of 7.5 mJ can be selected for assuring 10 dB of bistatic SNR along the whole orbit.

For this kind of system the use of three different antennas rather than a single active system is advised. In this case the central antenna can be designed differently from the other ones, by using, for example, a circular reflector RA-2 like with 1.3° of aperture while the antennas devoted to bistatic measurements can be realised as planar arrays.

In this case, the two planar arrays should be pointed according to the angles shown in Table 4and, of course, in a symmetric way on board of the two satellites.

Table 4. Three beams system: maximum and minimum values of the steering angles and optimal values of the antenna pointing angles

	Maximum value (°)	(°)	Minimum value (°)
Azimuth steering angle ϑ_x	0.155		0.118
Elevation steering angle ϑ_y	4.080		1.066
Azimuth pointing angle $\overline{\vartheta_x}$		0.136	
Elevation pointing angle $\overline{\vartheta_y}$		2.573	

THE Y AXIS LABEL SHOULD BE ALIGNED LIKE THAT OF FIG 6

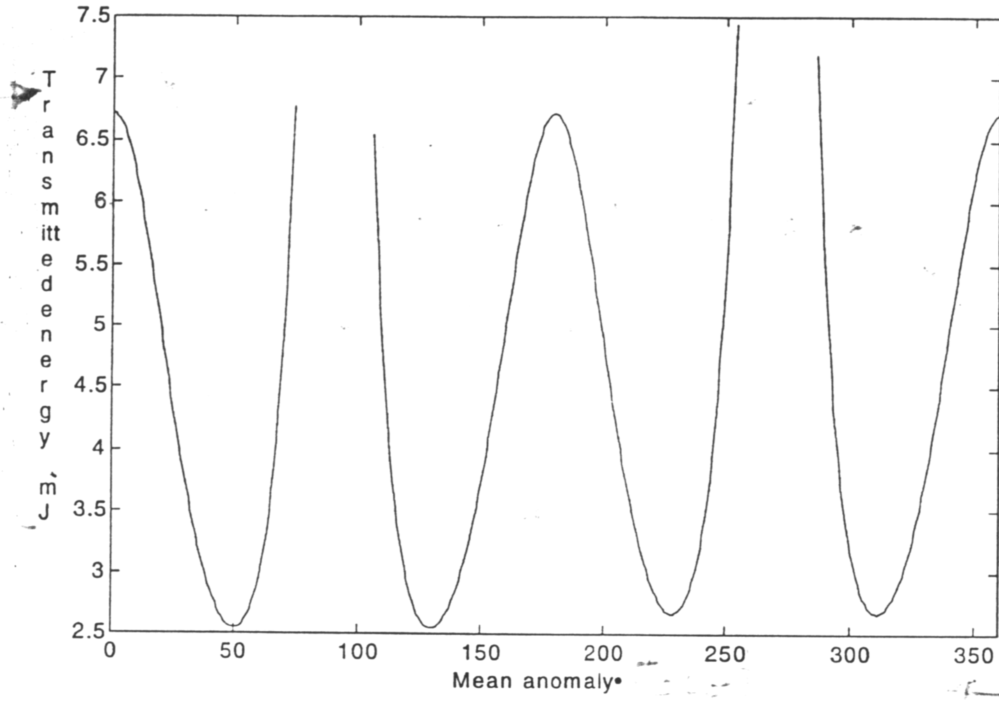

Fig. 5. Three beam system: minimal energy to be transmitted as a function of the mean anomaly along the orbit for assuring 10 dB of SNR

The opposite pointing angles in the azimuth plane of the two planar arrays entail a diversity between the two satellites of the bistatic pair which as a consequence means that they are not interchangeable. This possible problem can be overcome by neglecting the antenna pointing angles in the azimuth plane, reaching a preferable system configuration, accepting very small degradation in the final performances. In fact, the effect of this choice on the obtained SNR is shown in Fig. 6

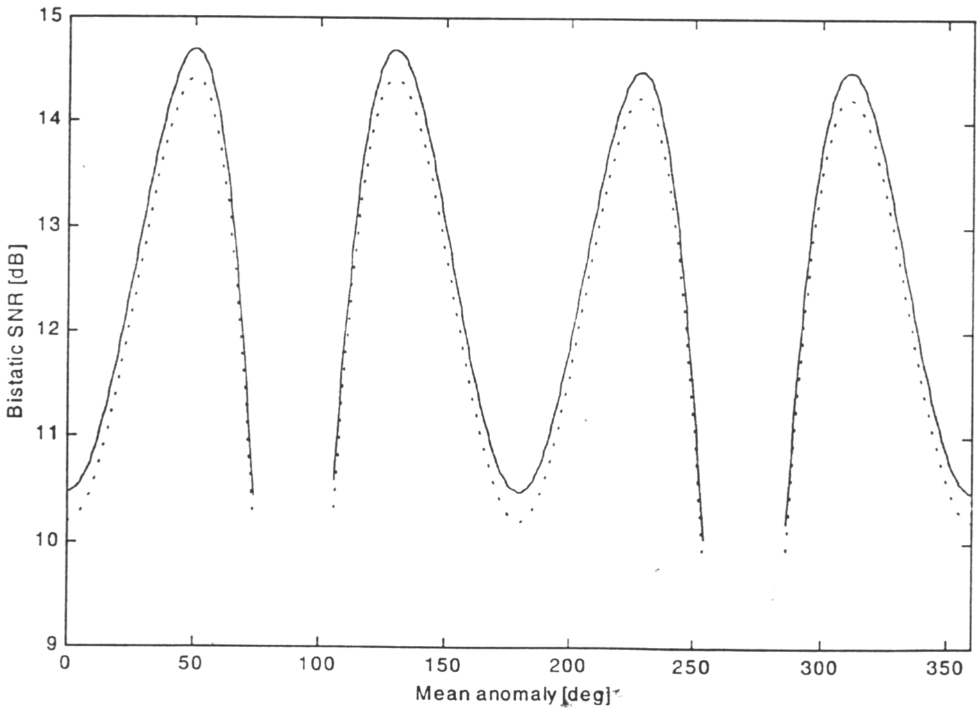

Fig. 6. Three beam system: SNR as a function of the mean anomaly along the orbit by considering an antenna pointing in the azimuth plane (solid line) and by neglecting it (dotted line).

which confirms that the decrease of the SNR level remains very small along the whole orbit, reaching a maximum value of just 0.25 dB.

Five beams system design

The operative configuration for this kind of system entails the use of two pairs of offset beams devoted to bistatic measurements, to be used alternatively on the ascending and descending part of the orbit.

For the same reasons of the previously analysed configuration, only pointing angles in the elevation plane have been considered. Moreover, in this case, since the use of an active antenna is surely preferable, a bidimensional beam steering would create so many difficulties in the antenna design that the resulting cost benefit relation would not be advantageous.

The pointing angles of the offset beams have been determined by minimising the difference with respect to the elevation angle of the bistatic point along the whole orbit. The result is graphically shown in Fig. 7 while Fig. 8 shows how to switch between the beams along the orbit to minimise the difference $(\vartheta_x - \overline{\vartheta_x})$ involved in Eq. (10) so that it remains within about $\pm 0.75°$.

The switching procedure allows also to obtain a unique value of 1.95° for the antenna aperture along the elevation direction.

Along the azimuth direction, as previously done, an aperture of 1.3° has been considered, since the optimisation procedure entails not feasible values. As a result, the energy to be transmitted by such a system for maintaining a SNR level of 10 dB is shown in Fig. 9 as a function of the anomaly. A value of 2.2 mJ should be selected if this level has to be maintained along the whole orbit, obtaining a final SNR along the orbit as shown in Fig. 10.

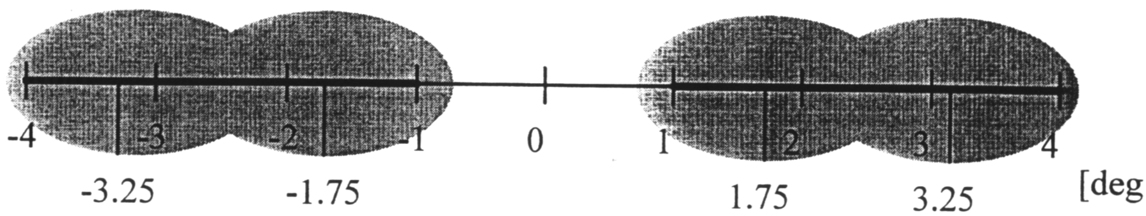

Fig. 7. Five beams system: antenna footprint distribution for the offset beams.

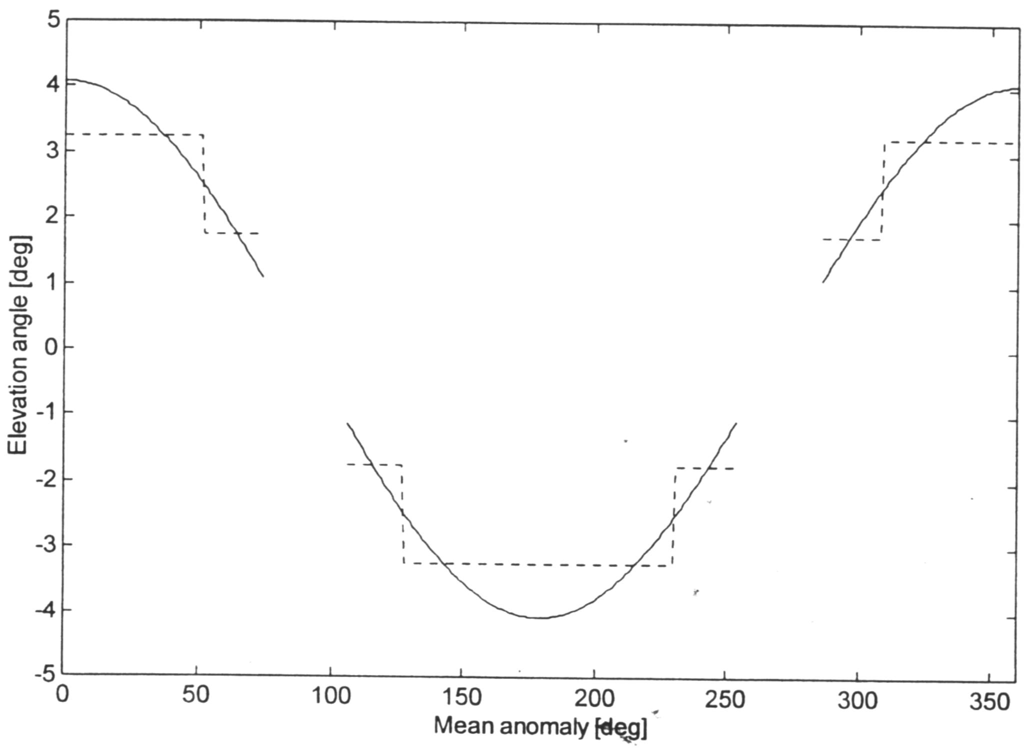

Fig. 8. Five beam system: switching procedure along the orbit for the offset beams.

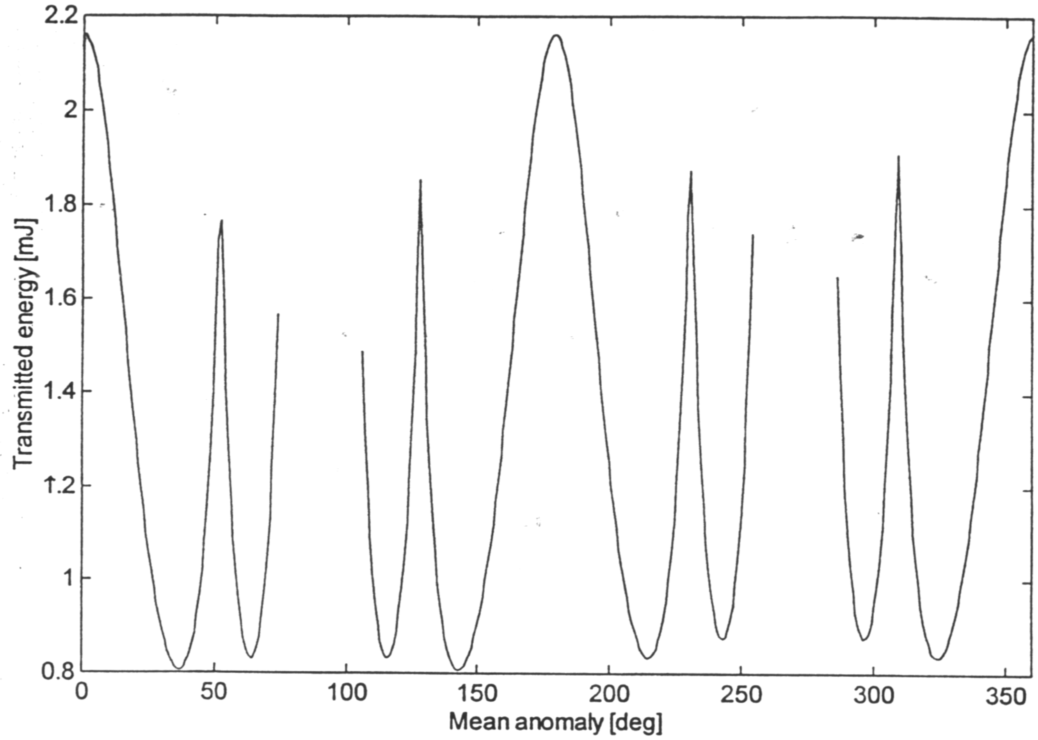

Fig. 9. Five beam system: energy to be transmitted along the orbit for obtaining a SNR of 10 dB.

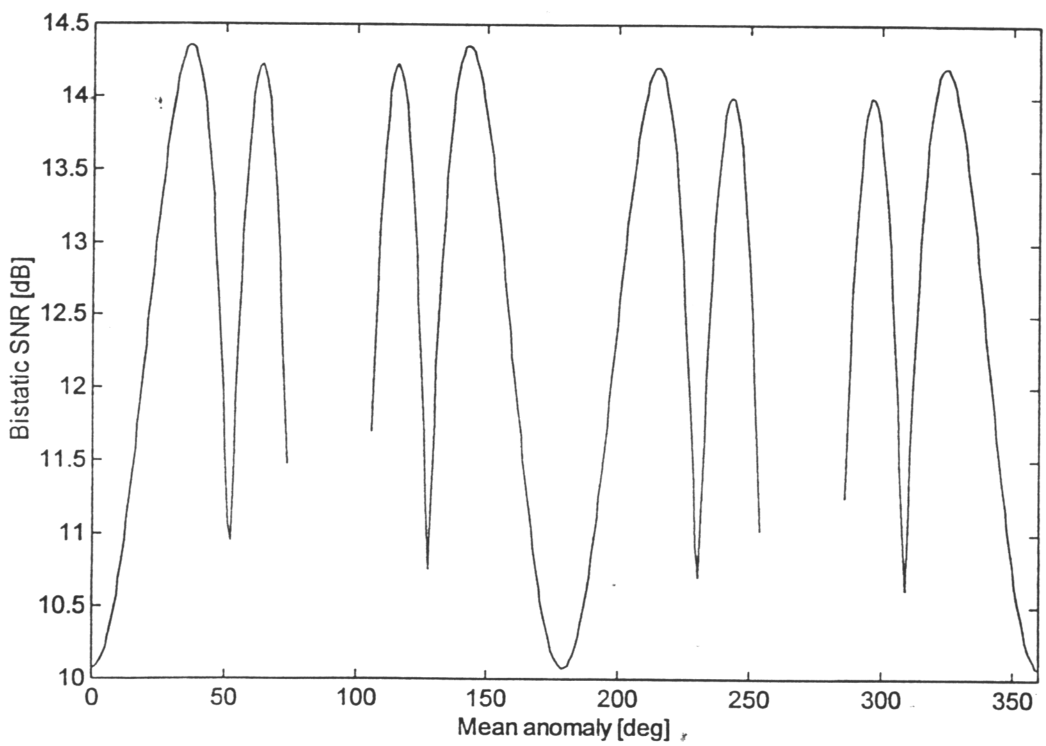

Fig. 10. Five beam system: bistatic SNR as a function of the anomaly along the orbit.

Seven beams system design

The same considerations previously done for the five beams system can be applied in this case. Fig. 11 roughly shows the footprints of the seven beams whilst Fig. 12 illustrates the switching procedure among the beams along the orbit. In this case the

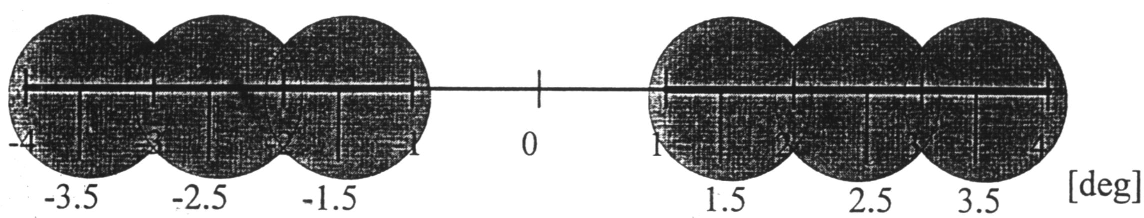

Fig. 11. Seven beam system: antenna footprint distribution for the offset beams.

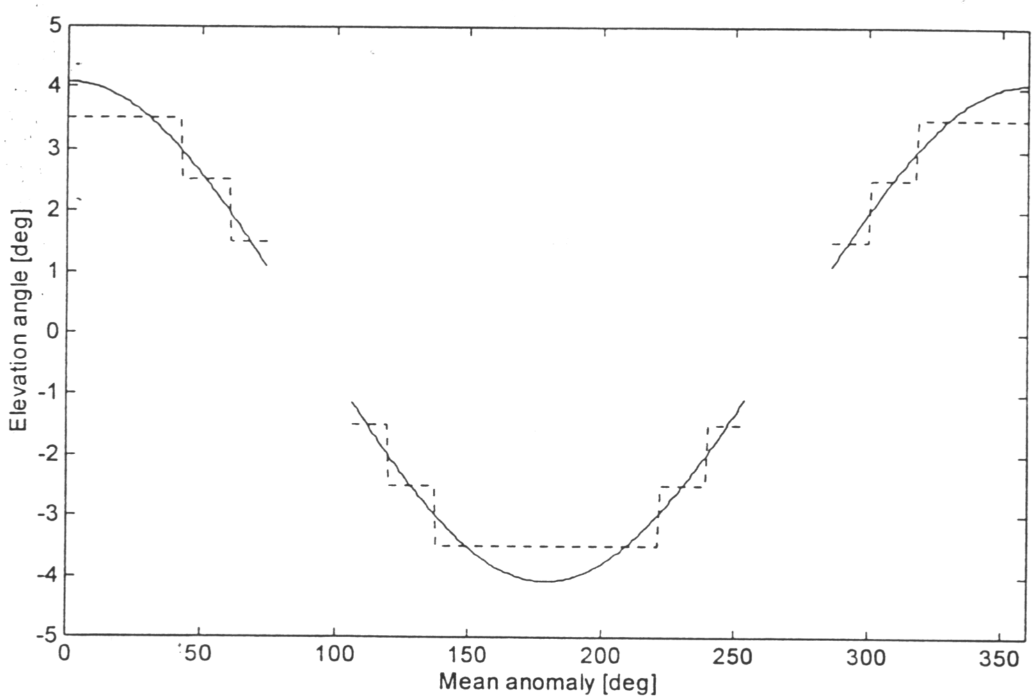

Fig. 12. Seven beam system: switching procedure along the orbit for the offset beams.

maximum value of the difference $|\vartheta_x - \overline{\vartheta_x}|$ involved in Eq. (10) is about 0.5°.

Once more, only pointing angles in the elevation plane have been considered. The optimisation procedure entails a value of 1.4° for the antenna aperture in the elevation plane enabling, therefore, the utilisation of beams almost circular and similar to that used for the RA-2 system. An energy of 1.1 mJ can be transmitted since it represents the maximum value of the required energy along the whole orbit, as shown in Fig. 13. The resulting bistatic SNR level is plotted in Fig. 14.

TIMING

Timing represents a critical point of the proposed system design since, in order to achieve adequate sampling of the ocean surface, the bistatic and monostatic measurements shall be almost simultaneous. The temporal separation (ΔT) between the two measurements, being a function of spacecraft altitude and bistatic angle, is given by:

$$\Delta T = \frac{2h}{c}\left(\frac{1}{\cos\vartheta} - 1\right) \qquad (15)$$

To enable detection of both echoes, ΔT should at least be equal to the radar pulse length which would result in it being too short for system power requirement. For examples, in our case the pulse length should be less than 13 μs for avoiding the superimposition of the mono and bistatic echoes along the whole orbit.

The possibility of performing a frequency separation has not been considered, since it would increase significantly the system complexity.

Therefore, the only possibility consists in shifting the transmitted pulse sequences t_{x1} and t_{x2} of the two satellites of such a time amount t_s as shown in Fig. 15. In this figure M_1 and M_2 represent the monostatic echoes received by the altimeter pair, while B_{12} (B_{21}) is the bistatic echo received by the

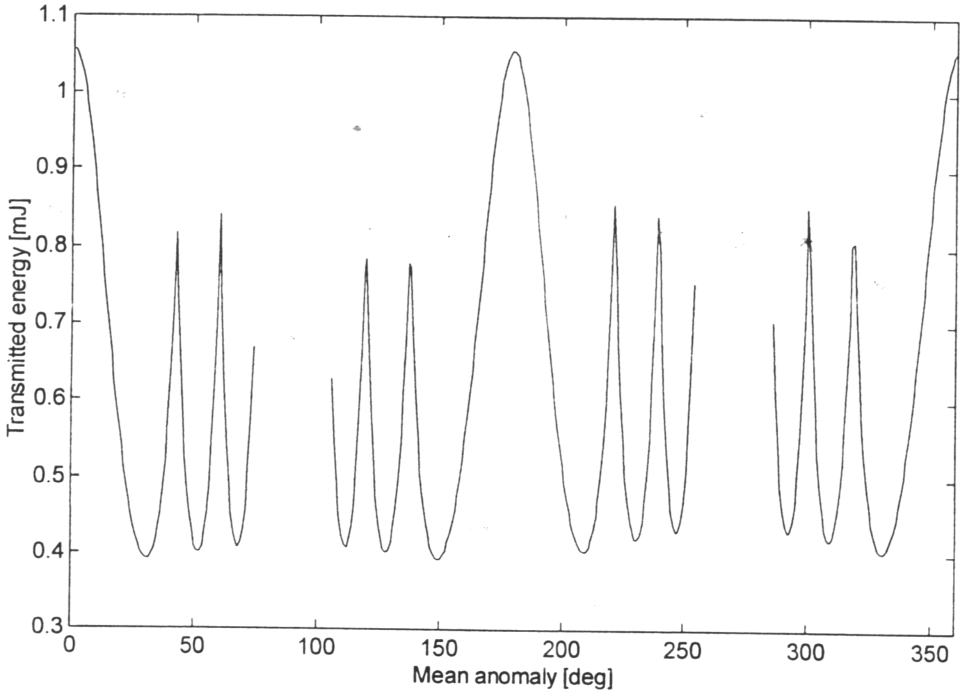

Fig. 13. Seven beam system: energy to be transmitted along the orbit for obtaining a SNR of 10 dB.

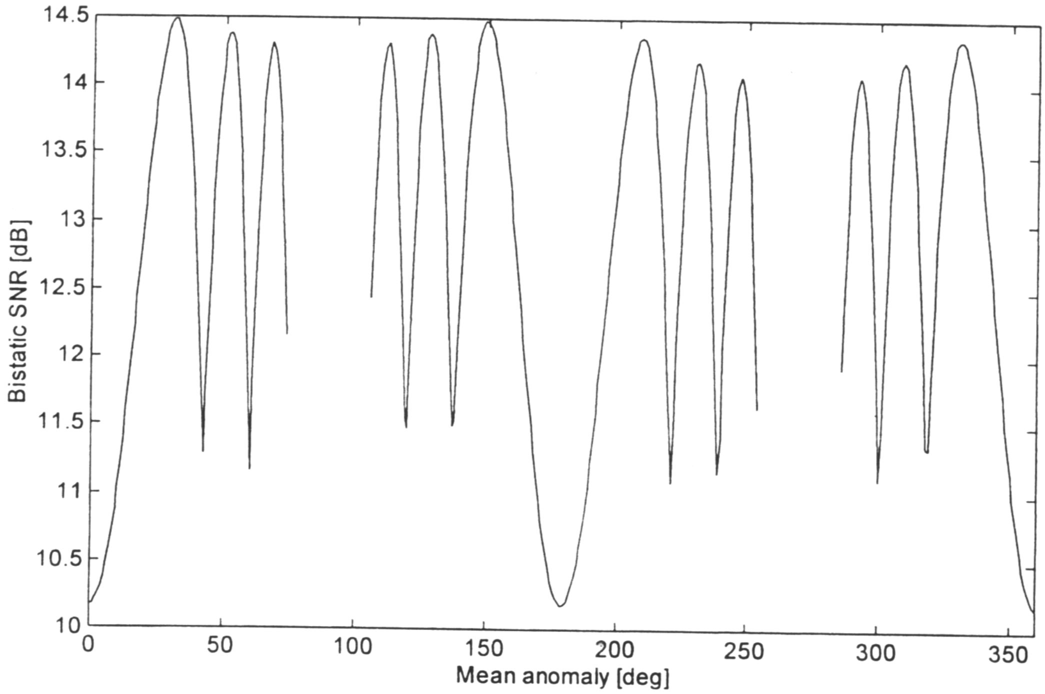

Fig. 14. Seven beam system: bistatic SNR as a function of the anomaly along the orbit.

second (first) satellite in correspondence to a pulse transmitted by first (second) one.

With respect to this kind of timing, the pulse repetition frequency (PRF) should be set to a value to respect the expected return times (t_m and t_b) and pulse duration (T) and to enable mono and bistatic measurements in both the altimeter systems.

Therefore, denoting with Δh the maximum foreseen variation of the distance between the radar and the surface and taking into account the ambiguity order (n), the following bounds can be derived:

$$\frac{n}{t_m^{min}-T-\Delta_l}<\mathrm{PRF}<\frac{n+0.5}{t_b^{max}+T+\Delta_r} \tag{16}$$

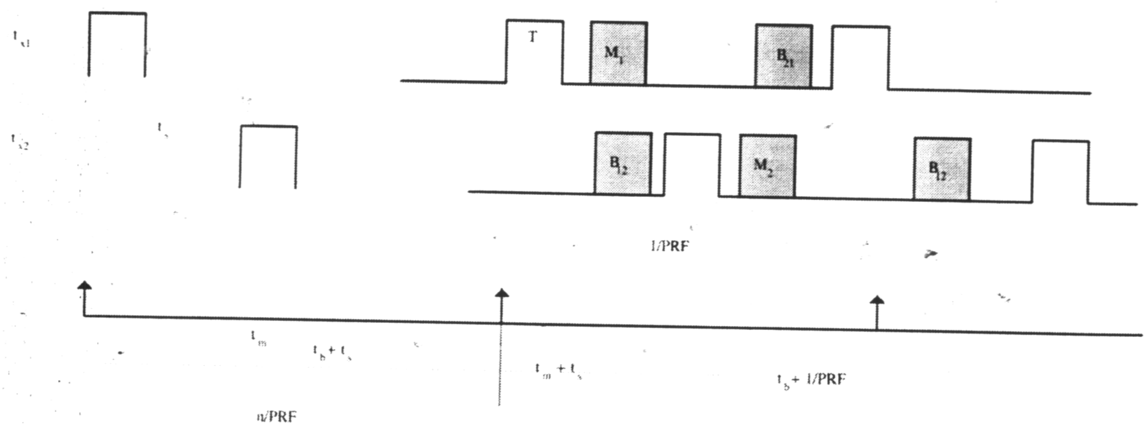

Fig. 15. Example of timing able to separate the mono and bistatic echoes.

with:

$$t_m^{(\min)} = \frac{2}{c}(h - \Delta h) \tag{17}$$

$$t_b^{(\max)} \approx \frac{2}{c}\frac{(h+\Delta h)}{\cos\vartheta} = \frac{2}{c}\frac{(h+\Delta h)}{\cos[\tan^{-1}(B/2h)]} \tag{18}$$

In the previous expression ancillary time intervals have been considered just after a transmitted pulse (Δ_l) and before it (Δ_r). In our mind Δ_r (= 10 µsec in the following) accounts only for commutation time while Δ_l (=40 + 2Δ_r sec in the following) should also enable the transmission of a 40 µsec S band pulse for performing the ionosphere bias correction like foreseen in the RA-2 system [5].

In order to enable suitable speckle reduction, a pulses averaging operation should be performed. Therefore, the timing system should aim to get the highest PRF value in order to allow the system to acquire the maximum number of correlated pulses [6] over a fixed integration time.

To have a reference, the RA-2 system integrates 100 pulses over each 60 ms.

To get high PRF values, the time shift t_s has been set in Eq. (16) to half the pulse repetition interval while the choice of the ambiguity order value requires a trade off between pulse duration and orbit variation. In fact, by increasing the ambiguity order, the maximum acceptable value of the variation between the radar and the surface decreases or, in other words, it can be maintained with a lower pulse duration. Conversely, the latter parameter value should be as large as possible due to the system power requirements underlined in the previous paragraphs. A suitable choice for the timing parameters is shown in Table 5.

Table 5. Suitable PRF values for the single pulse transmission case

Ambiguity order	5
Pulse duration	80 s
PRF	988 Hz
Maximum orbit variation	20 km
Averaged pulses over 60 ms	60

For the single-beam system, following the four possible choices shown in Table 3, the pulse length value of Table 5 implies a transmitted peak power of 25, 62.5, 125 and 500 W respectively. Once more, to have a comparison term, it can be useful to refer to the RA-2 system, that transmits a peak power of 50 W.

For the multi-beam system, some additional considerations should be done, since it is worth noting that in this case the coupling between the beam devoted to classical measurement of one satellite and the beams used for bistatic measurement of the other satellite is weaker with respect to a single-beam system, but, considering the small offset angles involved, a strong coupling can exist among the beams of the same satellite. This means that, also in this case, the pulses devoted to monostatic and bistatic measurements can not be transmitted simultaneously and that a delay should be still present between the two timing sequences. The latter is true independently if the beams are produced by the same active antenna or physically different ones. In other words it does not depend on the number of independent transmitting/receiving channels used.

In addition, as shown in Fig. 16, the transmission of a pulse for the bistatic measurement should occur alternatively on the two satellites. This is done by avoiding the superimposition of the bistatic echo with the one backscattered from the bistatic point.

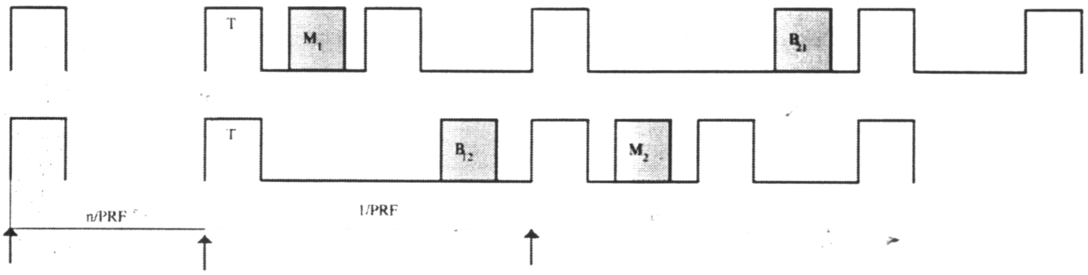

Fig. 16. Possible timing for multi-beam systems.

Therefore, the timing parameters of Table 5 can be still considered since the only difference from the timing of Fig. 15 is that, in this case, the bistatic measurements results are halved.

These values entail a peak transmitted power of 93.75, 27.5 and 13.75 W for the three, five and seven beams systems respectively.

CONCLUSIONS

A potential technique for improving, in reduced revisit times, the spatial sampling of ocean topography measurements from space has been analysed in this paper. The measurement approach foresees the use of a satellite constellation of radar altimeters able to provide nadir-looking monostatic measurements as well as bistatic measurements between tracks. This real innovative mission enables then to reduce the number of satellites otherwise needed by a constellation of conventional nadir-looking altimeters to reach the same spatial and temporal sampling and revisit time requirements.Quite simple constellation, constituted by an independent pairs of satellites, have however been considered in order to reduce the complexity of the payload which would also reflect in a complexity of the overall flight system. In fact, the key point in the design is represented by the amount of transmitted peak power and antenna configuration to accomplish the bistatic measurements because an implementation of an on-board mini-satellite is foreseen.

Change of the bistatic baseline with latitude along the orbit implies a continuous movement, in the majority of cases along the across track direction, of the bistatic reflection point on the ground. Therefore, in spite of their simplicity, nadir looking wide beam antenna systems demand either really high transmitted peak powers (order of hundred of watts) or wide antenna, not feasible for a small satellite configuration.

Multi-beam systems could represent an interesting solution but care should be taken of the increase in the instrument's complexity. A quite simple system can be designed, based on a nadir looking parabolic reflector devoted to monostatic measurements and two rectangular planar arrays symmetrically tilted in the elevation plane aimed to perform bistatic measurements along the orbit. The amount of peak power needed in Ku band is well feasible and it ensures a minimum of 10 dB SNR during bistatic operation and a really oversized figure for conventional nadir-looking monostatic.

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