Application of dual-frequency satellite altimeter data to improved global measurements of sea state

(INTAS/CNES 97-1291)

[Second periodic report: July 1999 - mid June 2001]

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European Space Agency (ESRIN), Frascati, Italy
Institute of Applied Physics (IAP), Nizhny Novgorod, Russia
Marine Hydrophysical Institute (MHI), Sevastopol, Ukraine

1. RESEARCH

1.1. Overview of Research Activities / Conformance with the Work Programme

The tasks specified in the first workpackage ('Development of a full physical sea spectrum model') have all been completed on schedule, except for task 1.6 ('Using computer model and/or analytical techniques to define the dependence of key wind/wave parameters'), which was delayed, but is now completed.

The second workpackage ('Development of a microwave backscatter model') has generally progressed well, with the exception of 2.4 which was delayed, because of its dependence upon task 1.6. On the other hand, the work performed in this section has extended considerably from the purely nadir-viewing geometry appropriate to altimeters to include angles significantly far from nadir (up to 40ß), which makes the models developed appropriate for analysing other spaceborne radar data, such as from a SAR (Synthetic Aperture Radar) or scatterometer.

The extension to a wide variety of test angles has been very helpful in validating the models of radar interaction with the sea surface. This is important since a model that matches well at nadir but not at inclinations far from nadir will not have got the physics correct, and thus not be so easily built upon by other researchers.

The third workpackage ('Development and testing of new wind/wave algorithms') referred to dual-frequency altimeters in general, but to-date there is still only one in operation (which has had some impact upon the schedule, see later). The task of co-registering buoy and 1Hz GDR data has been completed and used for developing and validating improved algorithms for wind speed, wind stress, wave height and wave period. The high resolution waveform data have also been acquired, but the task of co-registering with the buoy data is not yet complete. Initial examination indicates that it may prove very difficult to extract further information such as skewness from the waveform data.

No tasks in workpackage 4 ('Application of validated algorithms') have yet been started.

The work programme is being adjusted to include more analysis of non-nadir observations, because of the insight they are providing. Theoretical analysis has suggested possible improvements to the recovery of wave spectra from SAR data, which are to be tested with data from the C-band instruments on ERS-1 and ERS-2. This may be extended to Envisat data. We will also investigate X-band data from a Russian SAR which suggest a significant backscatter contribution from non-Bragg scattering.

The original work programme had scheduled a report to be written for nearly every task (16 reports in total). We have decided against that, instead devoting effort to conference presentations and proceedings, and where possible getting a wider dissemination of our results by seeking refereed publications.

1.2. Scientific Results

There have been several important results from the project so far.

The first is an improved model of the sea surface spectrum, including wave breaking, air flow separation and parasitic capillary waves; this has led to a number of submitted papers. (Kudryavtsev and Makin, 2001; Makin and Kudryavtsev, 2001)

The second step has been development in the modelling of radar interaction with the sea surface to include non-Bragg terms. This has required some adjustment to agree better with observed data, making the end result a semi-empirical model (Kudryavtsev et al., 2001a,b). A simplified version has been developed to provide quicker calculations (Karaev and Balandina, 2000) .

The development of an improved altimetric wind speed algorithm has been an important advance. Once evaluation is complete (Karaev et al, 2001a), this may provide an important long-term dataset for climatological studies.

The prototyping of an asymmetric 'knife beam' altimeter (Karaev et al., PORSEC 2000) is an activity not within the original plans, but could prove of great long-term value, if it helps in the design and development of the next generation of altimeters. Such a 'knife beam' altimeter can detect wave direction from space.

♦ Joint Publications of INTAS and NIS project teams

§ **International journals**

§ Karaev, V.Yu., M.B. Kanevsky, G.N. Balandina, P.D. Cotton, P.G. Challenor, C.P. Gommenginger, and M.A. Srokosz, On the problem of the near ocean surface wind speed retrieval by radar altimeter: two-parametric algorithm, accepted by Int. J. Remote Sensing, 2001a.

§ Karaev, V.Yu., M.B. Kanevsky, P.D. Cotton, and P.G. Challenor, Is it possible to measure ocean surface slopes with a microwave altimeter?, submitted to Int. J. Remote Sensing, 2001b.

§ Kudryavtsev, V., D. Hauser, G. Caudal, and B. Chapron, A semi-empirical model of the normalized radar cross-section of the sea surface. Part 1: The background model. (submitted to J. Geophys. Res.), 2001a.

§ Kudryavtsev, V., D. Hauser, G. Caudal, and B. Chapron, A semi-empirical model of the normalized radar cross-section of the sea surface. Part 2: Radar modulation transfer function, (submitted to J. Geophys. Res.), 2001b.

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§ **National journals**

§ (None)

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§ **Abstracts in proceedings (indicate invited publications)**

§ Karaev, V.Yu., M.B. Kanevsky, G.N. Balandina, C. Gommenginger and P.D. Cotton, On the problem of the wind speed retrieval by altimeter, Abstracts of Ocean Winds workshop, p.50, Brest, June 2000.

§ Karaev, V.Yu., M.B. Kanevsky, G.N. Balandina, C. Gommenginger, and M. Srokosz, On the problem of effective reflection coefficient at nadir probing of ocean surface, Specialist Meeting on Microwave Remote Sensing, 6-8 November 2001, Boulder, Colorado, USA (submitted).

§ Karaev, V.Yu., M.B. Kanevsky, P.D. Cotton, P.G. Challenor, C. Gommenginger and M.A. Srokosz, Two-parametric algorithm of the wind speed retrieval by altimeter data, Abstracts of TOPEX/POSEIDON and JASON-1 Science Working Team Meeting, 25-27 October 1999, Saint-Raphael, France, p.80.

§ Kudryavtsev V., D. Hauser, G. Caudal, and B. Chapron, A new composite model, including non-Bragg scattering effects, to model the radar NRCS and the radar Modulation Transfer Function, Abstracts of Ocean Winds workshop, p.53-54, Brest, June 2000.

♦ Publications without INTAS-NIS co-authorship of the project teams

§ **International journals**

§ Kudryavtsev, V., and V. Makin, The impact of the air flow separation of the sea surface drag, Bound.-Layer Meteor. Vol. 98, pp.155-171, 2001.

§ Makin V., and V. Kudryavtsev, The impact of dominant surface waves on the sea surface drag, Bound.-Layer Met., 2001 (submitted).

§

§ **National journals**

§ Karaev, V.Yu., and G.N. Balandina, A modified wave spectrum and remote sensing of ocean, (in Russian), Issledovanie Zemli iz Kosmosa, October-November 2000, N5, 1-12 .

§ Kudryavtsev, V., V. Malinovskii, A. Bol'shakov, and V. Smolov, Experimental study of mechanisms of radar returns modulation by wind waves, Issledovaniya Zemli iz Kosmosa (accepted), 2001, (in Russian).

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- **Abstracts in proceedings (indicate invited publications)**
- Karaev, V.Yu., The modified Bragg scattering theory for small and middle incidence angles, Proceedings of AP2000, Davos, Switzerland, 9-14 April 2000, 4pp.
- Karaev, V.Yu., and G. N. Balandina, Remote sensing of the ocean with a radar having an asymmetric antenna pattern, OCEANS 2001 MTS/IEEE , 5-8 November 2001, Honolulu (submitted)
- Karaev, V.Yu., M.B. Kanevsky, and G.N. Balandina, On the problem of measurements of surface slope at nadir probing, Specialist meeting on microwave remote sensing, Boulder, Colorado, USA, 6-8 November 2001 (submitted)
- Karaev, V.Yu., M.B. Kanevsky, E.M. Zuikova, V.Yu. Gol'dblat, and V.I. Titov, Experimental Measurements of Water Surface Slopes by Microwave Radar, Proceedings PORSEC 2000, Goa, India, December 5-8, vol. II, 863-865, 2000.
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♦ Books, monographs, internal reports, thesis, patents
- Karaev, V.Yu., M.B. Kanevsky, and G.N. Balandina, The numerical simulation of the sea surface and remote sensing, (in Russian), Preprint , N 552, IAP RAN, 26pp., 2000.
- Karaev, V.Yu., M.B. Kanevsky, and C. Gommenginger, On the problem of effective reflection coefficient at remote sensing of sea surface, Preprint, N 557, IAP RAN, 24pp., 2001.
- Kudryavtsev V., D. Hauser, G. Caudal, and B. Chapron, A semi-empirical model of normalized radar cross section: Background model and radar wave MTF, CETP Scientific Report, RI-CETP/4/2000, 50pp, 2000.
- Kudryavtsev V., and V. Makin, The impact of the air flow separation on the drag of the sea surface, KNMI reprints : 99-31, 16 pp., 1999.

	ALL PUBLICATIONS			ONLY: Jointly by INTAS and NIS Project teams
Scientific Output	published	in press/accepted	submitted	
Paper in an International Journal	1	1	4	4
Paper in a National Journal *)	1 (Russian)	1 (Russian)	0	0
Abstract in proceedings (conferences, workshops)	5	0	3	4
Book, Monograph *)				
Internal Report **)	4	0	0	2
Thesis (MSc, PhD, etc.) *)				
Patent				

*) Indicate the language **) Indicate if a report has not been published purely in order to protect intellectual property rights.

1.3. Impact and Applications (if appropriate)

There is not much that can be written on the impact to-date. The main direct impact will be on scientific understanding of the modelling of the sea surface and radar's interaction with it. However because of the time required for scientific advances to be reviewed and published, it is too early to evaluate the scientific impact.

We are currently investigating the possibility of patenting the concept of 'knife beam' altimetry.

2. MANAGEMENT

2.1. Meetings and visits

[Where possible the meetings have coincided with conferences or exchange visits to minimise their direct cost.]

'Kick Off' meeting (St. Raphael, France, 28th Oct 1999)

Attendees: G.D. Quartly, C. Gommenginger & P. Challenor (SOC), V. Karaev (IAP), V. Kudryavtsev (MHI)

Because of difficulties with visas and other commitments this meeting was much later than originally planned. Most management issues had already been resolved through exchanges by email and post, but this proved a very useful opportunity to meet co-researchers and acted as a '3-months progress' meeting. (INTAS funds also enabled V. Karaev to attend the TOPEX/Poseidon SWT meeting in St. Raphael on 25th-27th Oct.)

Progress meeting on development of sea state model (Paris, Dec. 1999)

Attendees: V. Kudryavtsev (MHI), B. Chapron (IFREMER)

Discussion of progress by two of the group working on workpackage 1.

Exchange visit of V. Karaev (IAP) to SOC (6th Jun. to 7th Jul. 2000)

To advance the work on theoretical aspects of radar scattering. It was hoped that a week of this period would be spent at a conference in France, but an appropriate visa could not be obtained.

Attendance of V. Karaev (IAP) at AP2000 meeting (Davos, Switzerland, 9-14th Apr. 2000)

Opportunity for V. Karaev to present his work at a highly relevant conference and benefit from discussions with other scientists.

'First annual review' meeting (St. Petersburg, Russia, 11-12th Jul. 2000)

Attendees: G.D. Quartly & C. Gommenginger (SOC), V. Karaev & M. Kanevsky (IAP), V. Kudryavtsev (MHI)

Since work on the project began on 1st July 1999, this was a '12-month review'. We discussed work completed and ran through the chief tasks for the year ahead, clarifying some of the uncertainties. (Meeting only required 1 of the 2 days scheduled.)

'Second annual review' meeting (Nizhny Novgorod, Russia, 11-12th Jun. 2001)

Attendees: G.D. Quartly & C. Gommenginger (SOC), V. Karaev & M. Kanevsky (IAP), V. Kudryavtsev (MHI)

A full review of the progress achieved to-date, plus discussion of the workpackages yet to be done. (Again, meeting only required 1 of the 2 days scheduled.)

Summary of meetings and visits

Visits	Number of scientists	Number of person days
West ==> East	2	8
East ==> West	2	29
West ==> West	0	0
East ==> East	2	5

Planned meetings

Visit of Dr. Karaev (IAP) to SOC June/July 2001
Visit of Dr. Kanevsky (IAP) to SOC Sept./Oct. 2001
Third 'annual review' meeting at SOC April/May 2002

2.2. Collaboration

- In your opinion, how intense was the collaboration among the different Contractors up to now?

Intensity of Collaboration	high	rather high	rather low	low
West <=> East	X			
West <=> West				X
East <=> East		X		

In addition, there has been significant collaboration between the group at MHI and those at CETP (France) and KNMI (Netherlands).

2.3. Time Schedule

Programme has run roughly to schedule, except for tasks 1.6 & 2.4 discussed earlier. The aims have expanded somewhat during the second year, and consequently many of the tasks in workpackage 3 are not yet complete. There will need to be some refocusing of effort to finalise the main algorithms and provide new wind/wave datasets over the length of the TOPEX mission.

Jason-1 and Envisat continue to suffer delays in launch, meaning that only a limited amount of data will be available for initial analysis before the project ends, and that there will be no climatologies produced from them. In return, the work programme will include further analysis of SAR data.

We are working to a rearranged schedule finishing in June 2002. At present, it appears very likely that we should have completed all the tasks that can be achieved by the final project meeting (probably in May 2002), and so should be able to tidy up the details and produce final report by the end of June 2002.

2.4. Problems encountered

Meeting arrangements: It has been difficult to get all participants together at the same time, due to either work commitments or visa problems. We have had no representative from IFREMER at either the Kick Off or either Annual Review meeting; however there is a strong bilateral link between IFREMER and MHI, so no action needed.

Telecommunication: Changes in contact personnel both at SOC and INTAS have led to delays in communication between INTAS organization and the project co-ordinator. (Named co-ordinator at SOC changed twice before project really commenced; contact in INTAS then changed twice in the first 12 months) Resolved by a number of email exchanges.

Transfer of funds: On one occasion money was withheld from IAP payment because paperwork did not concur with claimants' details. Resolved by email exchange with INTAS secretariat.

Entrance into Russia: For our visit in June 2001 it was much more difficult to get entry visas for UK/French personnel than it had been in July 2000. As they were eventually granted (a few days before the meeting), this is a minor matter; if they had been a few days later, the meeting would have had to be cancelled (or postponed for a long time) because of other commitments already scheduled. Obtaining visa required extra letters and documentation and visits, totalling several man days labour at both SOC and IAP. This was a waste of precious resources as the Russian authorities knew that the visit was for purposes of INTAS collaboration.

Problems encountered	**major**	**Minor**	**none**	**not applicable**
Co-operation of team members		X		
Transfer of funds		X		
Telecommunication		X		
Transfer of goods			X	
Other°°°°°°°°°°°°°°°Visas	**X**			

2.5. Actions required

Please be aware that continued obstruction to visits from INTAS states to NIS will undermine the efforts to improve scientific communication.

3. FINANCES (in EURO[1])

Contractor		**Cost Category**						**TOTAL (Euro)**
# *)	Name of Contractor *)	Individ. Grants Labour Costs	Overheads	Travel and Subsistence	Equipment **)	Consumables	Other Costs	
1	SOC			2,355			50	2,405
2	IFREMER							0
3	ESRIN							0
4	IAP	13,200	300	3,049	1,900			18,449
5	MHI	5,750	750	900	2,700	200	200	10,500
6								
TOTAL (Euro)		18,950	1,050	6,304	4,600	200	250	**31,354**

*) List the Contractors in the same order and with the same numbers as in the Work Programme.
**) Contractors from INTAS Member States are not allowed to spend money of this grant on equipment in projects up until calls 1999.

Note costs in table are for the period up to the2nd annual review meeting (mid June 2001) the costs of hosting that meeting and for various parties to attend has not yet been claimed for.

Totals against contractors differ slightly from the records on spreadsheet kept by INTAS, because on a number of occasions SOC has paid conference and/or travel costs for Karaev (IAP) when payments needed to be quick, or were easier to arrange that way (e.g. via credit card). These direct payments by SOC (for travel to St. Raphael and subsistence there, and attendance at Davos meeting) total 1689 Euro, and in the above table have been set against IAP costs, rather than against SOC to whom INTAS actually made the reimbursements.

After the above adjustment, spending appears well within the original plans The eventual cost of T&S (Travel and Subsistence) for SOC personnel will exceed original plan, as flights have proven expensive. However the T&S costs incurred by partners 2 and 3 will remain much smaller than originally planned. The labour costs will be less than planned, as there have not always been as many MHI people supported as envisaged. There is one additional cost to plans to come, and that is for the purchase of SAR data.

MHI’s expenditure on equipment included 2500 Euro for a Notebook (portable computer); IAP spent 1900 Euro on two IBM PCs. The ’other costs’ against MHI are for the organization of the First Annual Review meeting.

4. ANNEXES

Team: Southampton Oceanography Centre

Members: Dr. Graham Quartly, Dr. Christine Gommenginger, Peter Challenor, and Dr. Meric Srokosz

SOC have been collating a dataset of collocated dual-frequency Topex data and in-situ wind and wave measurements for the development of improved wind retrieval algorithms and to assess the potential for further sea and wind parameter retrieval from altimeter data. Three datasets were collated: (1) a dataset of nearly 4500 collocated data points between Topex and a world-wide network of 41 buoys, providing coincident measurements of dual-frequency NRCS and SWH, buoy wind and wave parameters for the years 1992 to 1998; (2) a small dataset of Topex measurements collocated with direct wind stress measurements on a drifting Weather ship in the mid-North Atlantic; and (3) a dataset of nearly 3200 collocated Topex/buoy data with coincident spectral information (including nearly 400 points with fully directional wave spectra) allowing the computation of higher spectral moments.

> Dataset (1) was used for the development at SOC of new algorithms for improved wind speed retrieval. A series of one-, two-, and three-parameter algorithms was produced using non-linear least square fitting procedures and Neural networks. Best results were obtained with the altimeter NRCS at Ku-band and the altimeter SWH. The new two-parameter algorithm eliminates the 0.6 m/s bias observed with the Witter & Chelton (1991) algorithm. The addition of SWH information marginally reduces the residual wind error (defined as the standard deviation of the residuals) by about 10% (down to 1.23 m/s) but allows some sea state dependence in the wind speed to be resolved (Gommenginger et al., 2001).
>
> Dataset (2) was used to provide independent validation of the dual-frequency wind stress algorithm proposed by Elfouhaily et al. (1998). Unfortunately, data quality issues related to the distortion of the airflow by the ship structure limited the number of reliable data points to less than 50 for a two-year period. The algorithm results showed good quantitative agreement with the in-situ wind stress measurements. The implementation of the same algorithm using dataset (1) revealed a discontinuity problem at a wind stress, u*, of 0.23 m/s, which is related to the two-branch formulation of the algorithm. This latter problem makes it impossible to implement the algorithm as it stands for the production of global wind stress estimates.
>
> Dataset (3) has so far been used to produce slope estimates collocated with the altimeter backscatter coefficients. This dataset has been made available to IAP to assist their theoretical investigations. The relationship between slope and backscatter has been examined in particular in relation to various types of sea conditions. This dataset will be further exploited for the completion of the tasks ahead when the retrieval of further sea state parameters is considered.

Work has been initiated in relation to the extraction of further sea state parameters directly from the altimeter waveform data, in particular skewness. A small dataset of Topex waveform data collocated with directional buoy spectra was collated in time for the 2nd annual review meeting using the waveform data already held at SOC. Further waveform data have since been obtained from JPL but have yet to be analysed. The first dataset includes 15 collocation occurrences for which the skewness parameter was estimated by integrating the buoy directional spectra. Our initial assessment points at the need for (a) careful treatment of spurious features in the Topex waveforms and (b) the development of a technique which allows us to compensate for the effect of SWH and wind speed on the waveforms.

Reference
Gommenginger, C.P., M.A. Srokosz, P.G. Challenor, and P.D. Cotton, 2001: Development and validation of altimeter wind speed algorithms using an extended collocated buoy/Topex dataset, *Accepted for IEEE Transactions on Geoscience and Remote Sensing*.

Team: IFREMER

Members: Dr. Bertrand Chapron, Dr. Jean Tournadre, J. Gourrion

The IFREMER group have used the scattering model of Elfouhaily to predict the mean relationship between backscatter cross-sections at Ku-band and S-band. This is providing the 'Day One' algorithm for rain-flagging of the Envisat altimeter, since rain-affected points should lie off the mean relationship. The IFREMER group have worked closely with team at Marine Hydrophysical Institute on on the development of theoretical models (see their entry)., but have also made many *in situ* observations to tie in with simultaneous altimeter data.

TOPEX altimeter data have been collected during the FETCH (Flux, Etat de la mer, et Teledetection en Condition de fetcH variables) campaign carried out in the Gulf of Lion area, of the Mediterranean Sea, from March 12th to April 15th, 1998. The objectives of the experiment included the study of wave growth characterization in fetch-limited conditions for the improvement of wave prediction models, and analysis of the relationships between microwave altimeter measurements and surface properties under strong wind and developing sea conditions. To achieve these objectives, instrumented aeroplanes and buoys were deployed during the period of observations.

In the past, sea state development in fetch-limited conditions has mostly been studied to characterize the lower frequency part of the energy, containing the developing wave spectrum. Using altimeter measurements, we can use both the altimeter cross section and estimated significant wave height observations to further characterize the expected rapid wave slope growth and saturation at the early stage of wave developments under strong wind conditions. For our purpose, we further emphasise the combined use of both C- and K_u-band TOPEX data. As is usually assumed, these measurements are closely related to the sea surface slope variance of the short gravity waves, with the main differences between C- and K_u-band being that K_u-band is more affected by diffraction effects and possible foam impact:

The data collected during the FETCH experiment have also been compared with selected high-wind low-sea-state data. At the early stage of wave development, both the FETCH data and the global observation show a very high correlation between cross section measurements and significant wave estimates. Most importantly, during active growth, for any given wave height, the overall roughness at C- and K_u-band scales is found to be almost independent of wind. As the fetch increases, the radar cross section decrease to a wave height dependent threshold.

Then the C-band cross section remains constant, while the K_u-band value still decreases but much less strongly than under the 'active fetch' range. This characterizes a 'developed' or 'mixed' range for which the longer waves develop but mostly under nonlinear interactions. The overall roughness as detected by altimeter instruments then tends to saturate, as the short wave spectrum reaches a statistical equilibrium. The 'developed' range occurs at greater fetch, and at greater wind speeds. However, this fetch distance is systematically smaller than the nominal distance for full development with the condition of a roughness equilibrium state being reached at different values of the wave age for different wind speeds..

Team: ESRIN (ESA)

Members: Dr. Jerome Benveniste

Jerome Benveniste's main r le has been in the provision of information, and helping the project to acquire data. A particular case was his guidance on ordering SAR data from ESA.

Team: Institute of Applied Physics

Members: Dr. Mikhail Kanevsky, Dr. Vladimir Karaev, Galina Balandina, and Emma Zuikova

IAP have been working on a simplified version of the Kudryavtsev spectral model, which allows quicker calculations. This version has been used to simulate the sea surface and to calculate the reflected signal (pulse waveform and NRCS) at nadir view. The existing scattering theory at nadir view was extended to take into account the form of radar beam. IAP have also devised a novel design of altimeter, with a 'knife beam' much broader in one dimension thanin the other. They have developed the scattering theory for such an instrument, showing how the NRCS will depend upon the relative orientation of the asymmetric beam with respect to the direction of wave propagation. A working prototype has been constructed and installed on a high bridge over the river Oka in Nizhny Novgorod. To take into account the influence of small ripples on the reflected power at nadir view, they have developed modified resonant scattering theory, which gives a better representation of the NRCS at small to moderate incidence angles (0ß to 20ß)..

The investigation of electromagnetic scattering for two radar wavelengths (2.1cm and 5.5cm) was carried out. The results have shown that it is possible to improve the precision of the friction velocity measurements using a two-frequency algorithm. However, we must have more information about scattering surface (sea surface) and know the truth connection between wind speed (U_{10}) and friction velocity in dependence on sea state (SWH and dominant wavelength). Simpler two-frequency algorithms of wind speed retrieval may be developed for Envisat (2.1cm and 9cm). A publication is being prepared on this.

The present work continues our research of electromagnetic scattering at small incidence angles. The elementary configuration of a radar permitting to measure slopes of surface is considered. The conventional altimeter has a size of footprint 15-20 km. For measurement of surface slopes we suggest to apply a Doppler radar with the asymmetric (knife-like) beam (for example, 1ß by 20ß-26ß), oriented along a track. The temporal delay is used forrange selection of the radar signal, and the sign of Doppler shift is used to distinguish the signals coming from points lying before and after the middle point of the radar footprint. The great advantage of the knife-like antenna beam in comparison with narrow radar beam, looking at any angle forwards on moving the carrier, is, that each surface segment we observe at all angles in an interval from —13ß to 13ß, i.e. the distribution function of slopes and slopes of a surface along a directionof movement are measured. Thus, having installed together with a conventional altimeter the simple radar with a knife-like beam, we can realise direct measurements not only of the significant wave height but surface slopes too. Comparing radar cross sections measured on one range, but differing by sign of Doppler shift it is possible to determine the asymmetry of the wave profile. The advantage of new radar is the simplicity of its construction and small size.

We consider the configuration of a radar permitting to measure a surface slope in a broad swath. The conventional altimeter has small footprint (15-20 km). For measurement of slopes it is offered to use a Doppler radar with the knife-like antenna pattern (for example, 1x20 degrees). The rotation of such antenna will allow to illuminate a broad swath (200-300 km), which will depend on flight altitude. All illuminated area is divided into small elements and the radar signal from each element is being analysed. For splitting on range the time of delay of a reflected signal, and on azimuth - rotation angle of the antenna will be used. The sign of Doppler shift (except for a direction across the radar track) will allow to distinguish positive and negative speeds. The minimal size of element, on which the slopes will be measured, will depend on an incidence angle. Thus, the radar image of a surfaces similar scatterometer image will be received. Each element we observe at various azimuth and incidence angles that deal with movement of radar and antenna rotation. Comparing radar cross section, measured at different conditions, we retrieve a slope on each element. By the following step we, shall define wind speed, taking into consideration the information about a surface slope. The additional information will allow to decrease the error of wind speed retrieval in comparison with present algorithms. The precision of determination of direction of wave propagation will depend on antenna speed of rotation. Because each element we shall see at various azimuth angles, it will be possible to determine a direction of wave propagation and asymmetry of the wave profile. Significant wave height along a track will be accessible, if the new radar will be dispose together with a altimeter.

For research of the process of electromagnetic scattering by the ocean surface and the development of remote sensing methods the computer code permitting to simulate the main states of ocean surface (wind waves, swell and mixed sea) was developed. The surface is being considered as the superposition of plane waves having different frequencies and random phases propagating at various azimuth angles. The outcome of the computer code is written in the file and then will be used for study of possibilities of measurement of ocean surface parameters by radar of the any configuration. The first comparison of model estimations with experimental results has shown that the program can be used for development remote radiophysical methods.

On the basis of the buoy data the research the influence of small-scale ripple (in comparison with an electromagnetic wavelength) on the power of a backscattered signal is carried out. The formula for an effective reflection coefficient for electromagnetic radiation with wavelengths 2.1 cm and 5.5 cm are obtained. It is shown, that the main factor influencing on power of a reflected signal is the slopes variance of large-scale waves. At the same time, the dependencies of effective reflection coefficient on friction velocity are different for different radar wavelengths. This fact can be used to improve the accuracy of the friction velocity retrieval by data of two-frequency radar.

Team: Marine Hydrophysical Institute

Members: Dr. Vladimir Kudryavtsev, Dr. Vladimir Malinovsky, Dr. Leonid Koveshnikov, Dr. Pavel Katkov, and Dr. Vladimir Kudryavtsev. (Note not all of these have been involved with the project all of the time, but all have contributed to the results of the group, and have been paid accordingly by INTAS.)

The groups at MHI and IFREMER have been developing a model of the growth and decay of waves and small scale ripples on the sea surface. This is done by modelling the surface as the sum of a streamlined surface and discontinuities in surface slope, which represent the wave breaking fronts where air flow separation (AFS) take place. The drag supported by individual breakers is presented as the result of pressure drop distributed along the forward face of the breaking front, and the total separation stress is obtained as the sum of contributions of breaking fronts at different scales. Their statistical properties are described with use of the approach developed by Phillips (1985). The model is completed by using the spectrum of wind-waves proposed by Kudryavtsev et al. (1999), which gives a self consistent dynamical system where the air flow and wind waves are strongly coupled. The model allows for the development of parasitic capillary waves on the front of the gravity waves. Due to AFS, the dimensionless roughness scale increases with wind speed, and the relative impact of AFS on the total surface drag grows as the cube of wind speed. At low winds viscous surface stress dominates the surface drag and the role of the form drag is negligible; whereas at moderate and high winds the reverse is true. At high wind speeds, AFS can explain 50% of the total stress.

In order to characterise the radar scattering from the sea surface a physical semi-empirical model has been developed, based on the short wind-wave spectrum described by Kudryavtsev et al. (1999). This new model incorporates not only the Bragg mechanism but also the non-Bragg scattering associated with reflection from elements of breaking waves, and can be used for calculating the normalized radar cross-section (NRCS) and the Modulation Transfer Function (MTF), which relates the modulation of the NRCS to the long wave steepness. The model has been used to predict the scattering of electromagnetic radiation (from C-band (5.3 GHz) to Ka-band (35 GHz)) incident upon the sea surface at a range of angles, covering the values typical for both altimeters (0ß) and Synthetic Aperture Radar (SAR) (24ß to 36ß) and at both HH and VV polarizations. Although the altimeter is a nadir-viewing instrument, this model has been evaluated for its scattering of obliquely-inclined radiation too, as the combination of validation at nadir and slant angles gives greater confidence in its applicability.

In collaboration with Bernd Jahne (Heidelberg University), Jochen Klinke (Scripps Inst. of Oceanography), Vladimir Makin (KNMI), Kudryavtsev has performed analysis of short wind wave spectra measured in lab. conditions in a wide range of winds and fetches. This analysis is based on the physical model developed by Kudryavtsev, V. Makin and Bertrand Chapron in 1999.

MHI have a large set of radar images of the oceans obtained from Russian satellite (X-band, VV, real aperture), with incidence angle in the range 20ß-40ß. These reveal that at smallest angles the NRCS exhibits a strong increase which is clearly different from Bragg scattering. This effect is probably due to the quasi-specular reflection; MHI will process the images to analyse this effect, and its dependence on wind speed and other conditions.

Note, part of the work performed by contractor 5 ('MHI')has been carried out at the Russia State Hydrometeorological University in St. Petersburg, as the resources there were more suitable for some of the tasks.