ACRAS
Advanced Concepts for Radar Sounders
Executive Summary Report
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Prepared by:

C D Hall	Astrium
Nick Walker	eOsphere
with support from the ACRAS Team:	
Rolf Scheiber	DLR
Kostas Papathanassiou	DLR
Wlodek Kofman	University of Grenoble
Alain Herique	University of Grenoble
Erhling Nielson	MPI
Kim Partington	Polar Imaging
Hugh Corr	BAS
Martin Jarvis	BAS
Arno Wielders	ESTEC

eOsphere Limited
3, Great Farm Offices,
West Woodhay, Newbury,
RG20 0BP, UK

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1. ACRAS AIMS AND BACKGROUND

The goal of the ACRAS project has been to investigate and demonstrate viable techniques for the mitigation of surface clutter and ionospheric disturbance for surface penetrating low frequency radar observations, within regions of ice on Earth, Mars and Europa. The key motivation behind this research is the potential for ground-breaking science related to the viability of life on planetary bodies and the threat to our own life through sea level rise here on Earth. There are almost certainly other areas of science that will benefit from the ACRAS study, including surveys of arid regions on Earth and frozen ground regimes.

The European Space Agency (ESA) has been very successful at developing and demonstrating techniques that have revolutionised our knowledge of the surface of the Earth and other planets. Much of the scientifically important information however, including dynamics, is only revealed by penetrating beneath the surface. The pathfinder MARSIS mission has provided a very clear pointer as to what can be achieved.

Low frequency radar offers the possibility of below surface investigations, however this becomes more challenging as the spatial resolution requirements become more demanding. Surface clutter and ionospheric disturbance both impact on measurements.

The specific objectives for ACRAS were defined as follows:

- Identify quantitative requirements for surface clutter and ionospheric mitigation in the light of our up-to-date knowledge of their properties in Antarctic, Mars and Europa environments;
- Identify the extent to which previous mission designs reach or fall short in addressing these requirements;
- Identify and assess promising techniques for surface clutter and ionosphere mitigation, considering both the along-track and across-track directions, taking into account modelling as well as sensor design and on-board and ground processing techniques;
- Broaden the assessment of the techniques to consider their implications in terms of mission trade-off issues including power, mass, payload complexity, etc;
- Solicit and review input from the international community via a workshop, feeding this into ESA’s selection of a strawman mission for more detailed analysis of selected techniques;
- Define, implement and test selected techniques, delivering software to ESA that they can use in future as a valuable test-bed for techniques and simulations, including a maturing mission design;
- Carry out a final trade-off, consolidate the three missions, and summarize conclusions and recommendations from the team for ESA, thus paving the way for future ESA Earth and Planetary missions aimed at exploring sub-surface environments.

2. OVERVIEW

The ACRAS studies have examined the instrumentation and possible science returns that might be brought from four potential missions involving sounding observations covering both Terrestrial and planetary bodies.

Of these, the strongest most detailed requirements were identified for a Terrestrial mission while the planetary missions which include Mars, Europa (orbiting Jupiter) and Titan (orbiting Saturn) were described in less detail.

Where possible the ACRAS team has built upon existing missions and studies. For the Terrestrial case, a strong and growing technology base exists for radar observation from space particularly in the microwave band. The team has used this base, coupled with the desirability of ice sounding observations being made at the lower frequency end of the radio spectrum, the ITU allocation of a 6MHz operating band at 435MHz (P-band)

The ability of the ACRAS team to give a reasonably precise description to a possible Martian sounder is currently awaiting more detailed analysis of results being acquired from the 2 separate radar sounders (MARSIS and SHARAD) that are currently in orbit around Mars. Similarly for Europa, the CDF study conducted internally by ESA has already identified a highly credible concept for a Europa sounder and has provided a strong base from which to move onwards to more complex options.

In the case of Mars, the ACRAS team has identified some possible requirements that might be identified for a mission to follow the two current missions, but the overall status is that with agreement from ESA, the ACRAS team is not undertaking a detailed review of a sounder for Mars.

In the case of Europa, the ACRAS team has identified some possible enhancements to the CDF sounder concept (the ELR radar) which could bring a useful additional science return from the mission in the form of off-nadir observations. Such observations could contribute to a better understanding of the bizarre scattering characteristics that have been observed in higher frequency observations made from the Araciebo radio telescope.

Noting the interest in a mission to Titan, an additional section has been included into the Final Report to provide a trade-off between two possible implementations of a mission based around the enhanced ELR radar (ELRR+). These options included either ELRR+ on an orbiter at 1200km, or ELRR+ on a balloon. Of these two options, the team recommends the orbiter as preferable for a first mission.

3. RECOMMENDATIONS

This section provides a set of recommendations that could be taken by ESA regarding the future directions for associated technology developments and mission design. It has been structured so that for each potential mission, the main recommendations and implications are presented and then for each of these, the key issues arising from these choices are discussed in a more detail. Following this, recommendations are provided regarding the clutter mitigation approaches that might be best used for the terrestrial and planetary cases.

It is important to note that these recommendations capture the conclusions reached at a particular snapshot in time. The subject that has been addressed by the ACRAS study is very much an evolving story.

3.1 Mission recommendations

3.1.1 Earth

Main recommendations:

The ACRAS team recommends a system based on an instrument operating at P-band with facilities for off-nadir clutter cancellation, and implementing a large antenna (area ≈ 80 – 100m^2) which could be either a phased array with multiple (typically 3 contiguous phase centres) across track phase centres or a large reflector with multiple across-track beams (typically 3 contiguous beams).

The team recommends that the option between across track phase centres or a large reflector be kept open while technologies develop and a decision only be made when this becomes logistically necessary.

Reasons:

From an initial total of eight distinct concepts, two candidates remain and are recommended for further consideration. One candidate is based around the use of a reflector antenna technology, while the other is based on the use of phase array technology. Currently there is no clear advantage between the two concepts. Therefore the ACRAS team recommends that both candidates be retained for further investigation while the associated technologies develop.

It is important to note that the ITU allocation of a 6 MHz bandwidth at P-Band (435MHz) is a key constraint driving the technology options considered. If, at some point in the future, this allocation is changed, then it would be necessary to review the choices made during the ACRAS project that have led to our overall recommendations.

A further aspect favouring the recommendation of P-band for a space based Terrestrial sounder mission is the possibility of re-use of antenna technologies currently being considered as candidates for an Earth Explorer BIOMASS mission.

Implications:

Mass and power budgets for the two candidates were analysed and presented. It was seen that the range of masses lies between 200 and 300kg while the powers range from 200 to 300W. None of these values is a particularly strong driver of the overall instrument payload compared with potential launcher capabilities.

The immediate trade-off space between the candidates is even closer where it was shown that the lower end of the mass scale associates with the higher end of the power scale. It is equally clear that accommodation within a low-cost launch vehicle can potentially be effected for each of the candidates.

3.1.2 Europa

Main recommendations:

The ACRAS team recommends a system based on the basic ELRR instrument with its instrumentation enhanced so that it is capable of providing both sounding observations in the nadir direction and off-nadir SAR-like observations of surface features.

Having reviewed the options for a sounder mission to Europa, the ACRAS team recommendation is that a mission to Europa should be based on an enhanced ELRR concept. It should operate at the same low frequency ~50MHz, and with the same pulse bandwidth (~800kHz) but with the enhanced radar design in order to provide an off-nadir viewing capability with electronic beam steering used to obviate any need for spacecraft re-pointing,.

Reasons:

The recommended concept could bring a useful additional science return from the mission in the form of off-nadir observations. Such observations could contribute to a better understanding of the bizarre scattering characteristics that have been observed in higher frequency observations made from the Araciebo radio telescope.

The recommended concept would not compromise the primary goal of a Europa mission which would be to determine the thickness of the ice-sheet which is thought to cover a water ocean. The ACRAS team agrees with this goal but has proposed an enhancement to the sounder that will enable additional measurements at the cost of modest increased instrument complexity.

It was also noted that the potential to undertake on-board processing will reduce the required data rate to Earth back to the nominal ELRR rate, it is therefore recommended that developments in low power on-board processor capabilities designed for use in intense radiation environments should be monitored/undertaken.

Implications:

The principal discriminators between the basic ELRR design, and the enhanced versions, is the 30% increase in mass associated with both the enhanced versions, and the possible increase in data rate. Of these two, the mass increase seems to be the more dominant issue and at this stage it is hard to judge whether that increase would be tolerable.

The DC power changes are non-critical and could if necessary be totally balanced by a small reduction in RF power level that would have a negligible impact on instrument performance.

3.1.3 Titan

Main recommendations:

The ACRAS team recommends a system based on the ELRR with off-nadir SAR-like capability (either identical with the Europa instrument recommendation or very similar to it, but with bandwidth enhanced to around 10MHz)

Reasons:

Three candidate sounder concepts were described for a Titan mission an orbiting sounding mission, an orbiting sounding mission with an additional off-nadir imaging capability, and a balloon based sounding mission,. From these options an orbiting sounding mission with an additional off-nadir imaging capability enhanced ELRR concept was selected for recommendation, which would provide extra science benefits in terms of its potential to provide global data in both sounding and imaging modes. The team concluded that these benefits would be worth the extra technological cost.

The density of Titan is unusually small, and causes its atmosphere to extend much further from the surface, so that an orbiting satellite must fly at a much higher altitude than over Europa. Therefore the team recommended that the satellite should fly at around 1200km above Titan compared with 200km above Europa.

Implications:

It was seen that the principal discriminators between the three concepts relate to science return, data rate and the possible need for a data relay capability, and instrument mass. The need for a data relay system coupled with limited and uncontrolled coverage detracts from the balloon based mission.

3.1.4 Mars

Main recommendations:

The ACRAS team recommends a system based on an instrument capable of operation at frequencies higher than MARSIS and SHARAD and with wider bandwidth than SHARAD and with provision in the instrumentation to provide across track clutter cancellation.

Candidate implementation concepts could be an instrument developed from the enhanced ELRR, or one based around a reflector antenna, or one based around a phased array. All concepts would need to use across track clutter cancellation.

Reasons:

The driver behind this recommendation is the need to complement and enhance the excellent performance, of the two sounders MARSIS and SHARAD which are currently orbiting Mars. Discussion within the team has indicated that at this stage, the provision of finer depth resolution is probably the most beneficial approach.

However, the design would need to operate with an appreciably wider bandwidth than the 10MHz used by SHARAD. A number of implementation criteria impact the selection of operating bandwidth. The science requirement that appears to follow, based on the data currently being acquired by MARSIS and SHARAD is for finer resolution data about structure near to the surface.

Three candidate concepts were examined in the final stages of the ACRAS project, a basic high frequency, wide band sounder (50MHz ± 10MHz) with contiguous beams on each side of nadir for clutter cancellation, the same basic instrument with electronic off-boresight steering and polarimetric capability, and a similar sounding-only instrument operating at a lower frequency (10MHz ± 5MHz). The associated concept review discussions considered that the benefits of the across track imaging capability (which has minimal impact on instrument complexity) could be sufficient to warrant its inclusion, while the polarimetric capability which doubles the data transfer task and significantly impacts instrument complexity, probably does not provide an adequate improvement in science return.

Thus from the perspective of science return, the ACRAS Team recommended a hybrid of the two higher frequency sounders in the form of the basic sounder with electronic off-boresight steering.. This combination of capabilities would provide extra data relative to the basic sounder without extra costs (mass, power, and data rate). The electronically scanned bore-sight would yield scattered power versus nadir angle to inform on size distribution of irregularities.

Implications:

It is noted that the mass and power budgets assembled here are radically different and larger than those presented as a part of the ELRR studies. The values presented for the Martian sounder were based on current technologies of the type proposed for the radar payload on Sentinel–1. As such, they are representative of well-founded values for a Terrestrial LEO spacecraft. It is possible that appreciable savings in mass and power could be made, given additional development and the significantly lower operating frequency.

At this stage in the design process it is possible to provide only coarse estimates of mass and power estimates for each of the concepts, and only an outline indication of the antenna structures. Therefore the scope of trade-off available at this stage remains as a discussion between a number of possible mission concepts with a subjective assessment of which might be the most promising.

3.2 Clutter suppression techniques

We summarise the main conclusions from the clutter suppression work as applied to the two distinct cases of terrestrial and planetary sounders.

After the ACRAS Workshop, the interferometric approach to clutter suppression was discontinued in terms of investigation by the ACRAS team. However, some attempts were made at using this technique by DLR from data recorded over Spitsbergen. From airborne sensors it is clear that this technique has some advantages, however for spaceborne sensors the technique is always going to be compromised by ionospheric effects which will perturb the radar signal by varying degrees on different repeat passes. Another rational behind the decision for the ACRAS team to put this technique to one side was the fact this approach was already being very adequately covered by the GISMO Team in the USA, with respect to ice sounding terrestrial missions. If the GISMO team publish encouraging results then this option would need to be brought back to the table to be considered again along with the other techniques discussed here.

With respect to planetary missions the ACRAS team have concluded that the absence of adequate navigation data means that multi-pass interferometric techniques are unfeasible.

3.2.1 Earth

Along-track:

The recommended technique is based on the use of aperture synthesis to reduce instrument response to signals received from along-track directions away from the nadir. Effectively the algorithm takes side-looking SAR processing techniques and applies them to nadir direction so that the depth profile becomes the equivalent of the surface echo signal seen by a conventional SAR implementation.

Of the possible approaches to signal integration, incoherent summation of returns has been rejected in favour of coherent summation. The impact of the two approaches was demonstrated, where information about internal layers was more evident in the incoherent case, while the bedrock was more evident with coherent averaging.

Two forms of algorithm for the implementation of coherent integration were considered, one based on unfocussed integration, the other based on focussed integration.

In both cases, complex amplitude data from a number of range-lines are summed to provide a stronger and more spatially localised signal.

In the unfocussed case, signals from range bins at equal ranges are summed to provide an enhanced response.

In the focussed case, account is taken of the change in range between the radar and a given feature location as the radar moves from sample position (location of the radar when a pulse is transmitted) to sample position along its trajectory. This enhancement to the processing algorithm is called range walk correction. In the ice sounding case, the correction also takes account of the impact of the refractive index of the ice on range walk correction. The impact of the correction for refraction at the ice surface was demonstrated.

It was found that the inclusion of the correction for refraction at the ice surface for a space-borne sounding geometry is only relevant for deep bedrock, whereas it is mandatory for airborne sounders

Across-track:

The radar hardware recommended by the ACRAS team to enable across-track clutter involves the implementation of either a multi-beam antenna structure or multi-phase centre antennas. Of these two approaches, the multi phase centre approach has been shown to be more attractive and much of the subsequent analysis has been based on a 3 phase centre implementation of this technique.

However, in the absence of real across-track data acquisitions, assessments of improvements in across track clutter suppression have been limited to predictions and modelling.

The following important requirement on the amount of across-track clutter suppression was established.

With a dynamic range of 50 dB, it must be possible to detect subsurface layers (or the bedrock) if the sub-surface signal is not less than 50 dB below the surface reflection. For a spaceborne scenario, the ambiguous co-polar clutter from 5 deg off-nadir angle (corresponding to an ice depth of 1400 m) must be suppressed at least by 37-38 dB. The integrated signal-to-clutter ratio ISCR must be better than 38 dB.

One can compare this number with results from a simple model where a nadir signal-to-clutter ratio (NSCR) decay (10dB when going from 1 – 10 deg). For the angular range of interest it was found from the analysis of airborne data that off-nadir signals decay about 10 dB within the first 3deg reaching 15 dB at 10 deg off-nadir. These numbers could be used to refine the NSCR model in the event that more detailed and specific performance analysis was to be carried out at some future time.

It should be noted that the off-nadir reduction in backscatter, particularly for co-polarisation, may be quite different for different ice zones (notably dry snow / Antarctica and northern interior of Greenland versus percolation and more temperate zones) and therefore our assessment of nadir versus off-nadir response may have limited applicability. Some measurements of this nadir versus off-nadir response for different ice facies would be important to obtain in order to fully understand the performance of the technique.

Ionosphere:

The ionosphere causes the phase and amplitude of signals passing through it to change as a function of the density of the electron clouds (TEC) on the particular propagation path. Over polar regions, the scale with which such changes occur is in the order of kilometres, with variations in TEC capable of causing phase variations at the rate of several radians per kilometre.

The mitigation technique analysed acquires a knowledge of the relative phase between successive sub-apertures, by measurement of the phases associated with particular features in the observed scene whose characteristics remain constant from sub-aperture to sub-aperture. These features are called “coherent scatterers”.

This technique has been demonstrated successfully using data acquired in an airborne SAR campaign over urban regions where there is a profusion of coherent scatterers. However, while attempts have been made to exploit the technique in ice sounding the absence of a useful number of coherent scatterers has rendered the technique unsuccessful (at least for the moment).

3.2.2 Planetary

Along-track

The ACRAS team recommends that along-track mitigation achieved through the use of the unfocussed processing approach envisaged for the basic ELRR concept should be used. This approach also enables the prospect of some useful along track resolution enhancement when the data is received back on Earth.

The Team recommends that range cell migration correction should not be adopted for planetary missions because its benefits are not apparent until much higher levels of along track resolution enhancement can be realised, and the impact of such improvement could not be realised without a large increase in data transfer rate.

Across-track:

The ACRAS team recommends that 3-phase centre mitigation techniques could be implemented to provide some across track clutter mitigation. Additionally, the Team recommends that the 3-beam concept of operation that appears to enable both clutter mitigation and the acquisition of across-track surface data, could form the subject for more detailed study.

The hardware implications of this approach to across-track clutter cancellation would require only a relatively small redesign of the basic ELRR concept. The earlier work has outlined two stages of development:

- Involving across-track beam steering in association with a single receive chain (which maintains the data transfer rate at the same level as the basic ELRR design,)

- Involving across track beam steering in association with a multiple receive chains, one for each antenna phase centre (which increases the data transfer rate.

The analysis presented described how the 3-phase centre clutter mitigation techniques can be implemented without resort to the extra mass of 3 additional transmitters, but with a small impact associated with the extra mass for a 3-way splitter of transmit energy to each of the antenna elements, two additional Tx/Rx multiplexers, and 2 additional receive channels.

Furthermore the 3-beam clutter mitigation technique has to be implemented using electronic steering of the transmit beams, while avoiding the need for 3 separate receive beams. Therefore, the additional hardware requires 3 (lower power) transmitters with associated low power phase shifters, 2 additional Tx/Rx multiplexers, and a 3-way combiner to feed a single receive channel.

Ionosphere:

The ACRAS team recommends that there is little need of autofocus algorithms in the planetary context, and that even if there were such a need, then the probable absence of coherent scatterers on the surface or within such bodies would inhibit their utility.

3.3 Additional topics addressed late in the study

3.3.1 Ganymede

Additionally, at a late stage in the study, a further planetary body, Ganymede, has been identified as a possible target for future investigations. Ganymede is the outermost of the Galilean satellites of Jupiter and orbits at a distance of some 1.1×10^6 km from Jupiter compared with 0.6×10^6 km for Europa. Further studies should investigate whether the increased distance would render a Ganymede sounder less susceptible to radiation damage and possibly capable of improved performance if the radio noise environment is quieter at the Ganymede orbit.

3.3.2 Across track clutter mitigation using a possible 3-beam approach

A possible alternative means of achieving across track clutter suppression was identified very late in the study, which is applicable to both the Europa and the Ganymede missions. The technique makes use of the coherent relationship between echoes retrieved from nadir, left, and right hand sides of the ground track that obtains for the ELRR when associated with the electronic scanning techniques described as enhancements to the ELRR.

The team has noted that the technique has not been investigated in adequate detail. However, noting its potential to provide a level of across track clutter mitigation, and the possibility of returning off-nadir surface image data to Earth without increase to the data transfer link, the team recommends that future work should investigate the concept in greater detail to establish its pros and cons.