Considerations and requirements regarding WP5: Interferometry

César La Hoz   Tom Grydeland

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1 Requirements re baselines

In the terminology of the imaging technique, the true image in the scattering region is called "the brightness (distribution)" while its Fourier transform, measurable in the aperture plane, is called "the visibility function (or distribution)" (*Woodman*, 1997). Each pair of antennas, separated by a distance (vector) $\boldsymbol{d}$ measures the visibility (complex normalized cross-correlation of the signals in the two antennas) at the point $\boldsymbol{d}$ in the visibility plane.

The magnetic field geometry at high latitudes means that there are no inherent symmetrical directions in the brightness distribution, so full 2D imaging must always be made. This means that the baselines available must cover all scales from the shortest to the longest, and in all horizontal directions.

1.1 The shortest baselines

The shortest baselines define the largest unambiguous angle that the imaging can resolve. If the shortest baseline is too long, features at the edge of the brightness distribution will be folded (aliased) into the remainder of the image. This holds even if these features originated in sidelobes of the transmit and receive beams.

A baseline of $\lambda/2$ provides an unambiguous angle from horizon to horizon along this baseline, but antenna elements placed more closely together than λ typically have unacceptable coupling between them.

Since the baseline results from the centres of the array 'sections' (corresponding to Jicamarca 'modules' or AMISR 'panels') used to collect the signals, the size of these sections place a practical limit on how short the shortest baseline can be. The array should allow for collecting signals from

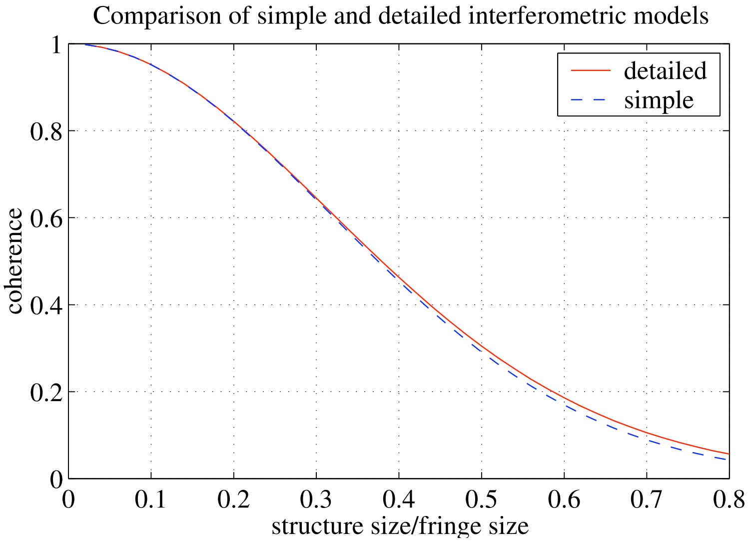

Figure 1: Coherence vs. structure size

neighbouring sections for the shortest possible baselines, and this capability must be included from the beginning.

1.2 The longest baselines

In contrast, the longest baselines define the resolution of the imaging. Smaller structures give higher coherences for baselines of any length, but there is little point in having baselines so long that structures as small as those we can reasonably expect to see will not have an observable coherence.

The smallest physical structure we can expect to scatter will occur in the auroral E-region. Optical studies have observed structures down to some tens of metres in the visible aurora (*Trondsen and Cogger*, 2001). A useful target resolution is therefore a structure of width 20 metres at 100 km range ($\theta = 2 \cdot 10^{-4}$). From figure 2 of *Grydeland et al.* (2004), reproduced as Figure 1 here, we can see that to reduce the coherence of such a target to 0.6, we will need a baseline (in units of radar wavelength) of approximately

$$A \approx 0.3/2\theta \approx 750,$$

which corresponds to 1000 m at 225 MHz. To reduce the coherence of a 10 m target at 100 km ($\theta = 1 \cdot 10^{-4}$) to 0.8, the corresponding baseline is $A = 1000$, corresponding to 1350 m at this frequency. Since a contiguous receiver array may turn out to be designed smaller than these lengths, the antenna, receiver system and signal processing designs should allow for the construction of array ‘sections’ outside the main array to produce the longest baselines necessary for fine resolution in imaging, cf. ‘the 65th module’ used at Jicamarca (*Hysell and Woodman*, 1997). Even if such extra sections are not included in the initial design, the design should allow for such sections to be added later.

1.3 Total number of baselines

Since the majority of baselines will be formed within the main array of the receiving antennas, the geometry used for these antennas will necessary constrain which baselines can be formed. Therefore, the number of baselines necessary for imaging might be slightly higher than if the baselines could be placed arbitrarily.

With a shortest baseline (in any direction) of 6λ, we should get visibility samples at seven different scales: 6, 15, 30, 60, 150, 300 and 750λ. Allowing for three receiving sections at each of these scales, we should initially plan for about 20 sections, which produces just over 150 baselines. As suggested above, the architechture of the system should allow for using a smaller number of sections initially, and for adding more sections later, if this is shown to be necessary.

For comparison, 1-D imaging at Jicamarca uses 7 modules at distances up to 400 m, yielding 21 baselines (in a projected geometry) from 2.2 to 94λ.

2 The placement of antenna elements

2.1 Active/passive vs. active and passive elements

Using separate antennas (or antenna elements) to transmit and receive means building two antennas of comparable complexity and size. One great advantage is that this allows for CW transmission with range resolution achieved using techniques adapted from passive radar (*Sahr and Lind*, 1997). Separate TX antennas means that a T/R switch cannot be used, and isolation from the transmitter must be achieved through other means. In passive radar, this isolation is achieved geographically, typically using an intervening mountain or > 100 km separation.

If the transmitter and receiver antennas are colocated, achieving sufficient isolation from a CW transmitter will be very difficult, and noise in the transmitter will mask the scattered signal regardless of dynamic range in the receiver (*F. D. Lind*, private commun.)

In passive radar (or a similar configuration with CW transmission) every sample contains signal from all ranges. This means that the sidelobe level of the transmission ($-40\,\mathrm{dB}$ for FM radio) relative to the strongest scatterer in the entire field of view of the radar defines a clutter floor — no scattering weaker than this clutter floor will be visible. In the presence of numerous artificial or natural strong scatterers (e.g. satellites or PMSE) this might be unacceptable.

Furthermore, the IS radar community has long experience with pulsed mode radar, and sophisticated techniques have been developed to use even quite high duty cycle transmitters to good effect. The radar should therefore be possible to use in pulsed mode, even if CW operations are going to be an important part of the observational schedule.

The receive antennas are going to be modular and suitable for interferometry. If the transmit antenna is also modular, it should be considered whether the transmitter modules should be possible to use as receive modules when the radar is used in a pulsed mode.

2.2 The receive modules

All the work on optimization of antenna arrays that we are aware of are from radio astronomy, dealing with the receive-only situation. If the same array is going to be used to transmit, the array must be optimized for two different beams.

Although capabilities for interferometry is an important criterion in the design of the radar, its ability to observe regular incoherent scattering should not be inhibited, and this should be accounted for in the placement of receive modules.

On the receive side, for the purpose of volume scattering, the most important criterion is collecting area. Therefore, for receive purposes, there is no inherent reason why the modules must be collected in a dense array.

3 Considerations which touch upon other Work Packages

3.1 Regarding WP3/WP6: the active element

For imaging, it is often desirable to have a wider illuminating beam. If the transmitting antenna is a phased array, it is possible to widen the transmitted beam in different ways:

- If a portion smaller than the full antenna is used to transmit, the beam will be wider, but this might limit the available transmit power.
- The aperture can be coded in a way similar to complementary codes, and after a small number of pulses, the resulting beam in the integrated data is as if the antenna sub-element was used to transmit the full power (*Woodman and Chau*, 2001).

Similarly, but not directly related to imaging — if the transmit antenna elements can be modulated arbitrarily in phase and power, sophisticated beam shaping can be used, e.g. to lower sidelobes or to adaptively place nulls in directions of unwanted scattering, e.g. to minimize the effect of satellites.

3.2 Regarding WP4: phased array receivers

For imaging, we need to process the data stream from receive antenna 'sections' before the stage where beams are formed from the entire array. (Beams can be formed for each section before processing for imaging.) If the beam forming for the entire array is to be performed in VLSI or FPGA circuits, it will be necessary to provide alternate data channels from antenna sections for imaging purposes.

To provide flexibility for different imaging applications, it should be possible to combine receive sections in various ways. Some applications may require only a few, but relatively large, sections, while others require a larger number of smaller sections in more complex geometries.

For the imaging setups in use today, it is good enough if the sections are defined and configured at experiment start. For an adaptable system, however, it would be better if the sections for imaging can be redefined and reconfigured while the experiment is running, e.g. to deal with sudden changes in the scattering properties of the medium.

3.3 Regarding WP9: Signal Processing

For interferometry of all sorts, the signal processing described in the objectives of WP9 must include provisions for cross-correlations and cross-spectra between any and all pairs of antenna sections used for interferometry. The computational requirements for this processing could quickly exceed those used for the regular (beam-oriented power spectra) processing, particularly when the number of sections used for interferometry grows.

The joint project meetings between WPs 4, 7 and 9 in months 6 and 9 should also include WP5 to ensure that the special requirements regarding signal processing for interferometry are understood and taken into consideration at all stages of this work.

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