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Communication

The NMR multi-transmit phased array: a Cartesian feedback approach

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Abstract

The use of Cartesian feedback is proposed to solve the problem of using an array of coils for the purposes of transmission in magnetic resonance imaging. The difficulties caused by direct and sample-mediated coil interactions are briefly examined, and the known solutions of using power-mismatched pre-amplifiers and transmitters noted. It is then shown that, without loss of transmitter efficiency, a high effective impedance may be created in series with each coil in the array by the use of Cartesian negative feedback. A bench experiment is described that confirms the theory. The solution is also viable for signal reception and is more efficacious than pre-amplifier damping, albeit over a smaller bandwidth.

Keywords: Phased array; Transmission; Damping; Electronic feedback; Cartesian feedback

1. Introduction

The use of phased-array coils in certain specialised areas of magnetic resonance imaging is now well established [1] and it is clear that as field strengths continue to increase, their use will become more prevalent. At least for signal reception, they yield, over elongated volumes of interest, a more homogeneous spatial response function and/or improved signal-to-noise ratio (S/N). In addition, they may help to counteract propagation effects that are seen at high field strengths [2], e.g., field-focussing in head images at 8 T. From their inception, however, it was clear that electromagnetic interactions, both direct and via the intermediary of the patient, presented problems, as these detuned the coils and introduced correlations between noise voltages [3–5]. During reception, these interactions are typically tackled by annulling nearest-neighbour *reactive* components, either by overlapping the coils or by the use of various bridges [6,7]. Despite the availability of venerable four-quadrant bridge designs that also remove the *resistive* components [8,9] of mutual impedance, these are not usually employed as the resistive cancellation degrades signal-to-noise ratio (S/N) and increases noise correlation. Rather, the transformation properties of each coil's tuning and matching network are then utilised in conjunction with low input impedance pre-amplifiers to present a large impedance in series with the coil [1,10,11]. This blocks residual resistive current flow in nearest neighbours and is also effective against the smaller combined (resistive and reactive) induced voltages in distant neighbours. The deleterious effects of the interaction are thereby rendered negligible. Note that decoupling methods external to the coils have also been described [12].

During transmission, an equivalent strategy is to retain the cancellation of nearest-neighbour reactive coupling but to mismatch grossly each transmitter so that each effectively presents a high impedance in series with its coil [10]. Up to a point, this can be done without

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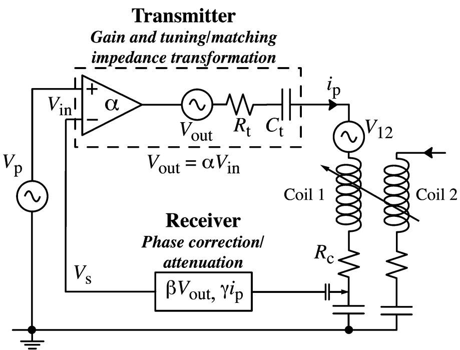

Fig. 1. The essence of transmitter output impedance transformation and Cartesian feedback. Sampling the current i_p that flows and applying a fraction γ of that current as negative feedback creates a high output impedance transmitter, as described in the text.

excessive loss of efficiency. Assume that when the transmitter output impedance is transformed by the coil tuning and matching network, its output impedance becomes resistance R_t in series with a capacitance C_t that contributes to the series tuning of the coil, as shown in the upper part of Fig. 1. Then if the coil's effective resistance (we include sample losses) is R_c, the transmitter is power-matched when $R_t = R_c$. If the transformed EMF from the transmitter is V_{out}, a current $i_0 = 0.5V_{out}/R_c$ flows. Now let the output resistance R_t of the transmitter vary by changing the transformation. By conservation of energy, the EMF changes by a factor $(R_t/R_c)^{1/2}$, current i_p now flows and the *relative* current becomes

$$\frac{i_p}{i_0} = \sqrt{\frac{R_t}{R_c}}\frac{2R_c}{R_t + R_c}. \tag{1}$$

If one is prepared to tolerate a 30% loss of the B_1 field strength associated with the current ($i_p/i_0 = 0.7$), then from Eq. (1), the transmitter resistance R_t may be increased to nearly $6R_c$ which reduces the Q-factor by a factor of 3.5 relative to the matched state. However, while being potentially useful (see below), this technique is by itself inadequate for use with arrays, and so other means are needed effectively to increase the transmitter source impedance. The solution we present here is the use of Cartesian feedback.

2. Cartesian feedback

Cartesian feedback, as it is now known in the communications industry, was first mentioned in the context of magnetic resonance in 1989 [13]. It is described more fully in the preceding Communication [14]. Essentially, during transmission the current in an array coil is monitored and compared in amplitude and phase with that desired—the current that would be present in the absence of interactions. Any error is corrected by the mechanism of negative feedback, the bandwidth of the transmitter chain and power amplifier being severely restricted to prevent oscillation. In this preliminary Communication, we shall consider for simplicity just two interacting coils, each being connected to its own transmitter. The second coil is being fed power, and our goal will be to block in the first coil the flow of current created by coupling. If this can be accomplished, then the presumption is that the technique can be extended to multiple coils and that as the system is linear, any desired current can be created in any coil, up to the limit of transmitter capability.

We first assume that our two coils have been tuned and matched in the temporary absence of couplings and that we also have available a small voltage $V_s = \gamma i_p$ that is representative of the current i_p flowing in the first coil, as shown in Fig. 1. Note that proportionality constant γ, which we may set as desired, has the dimension ohms. If coil 1 were isolated so that it had no coupling, we mark for future reference that we could write

$$V_s = \gamma i_p = \gamma \frac{V_{out}}{R_t + R_c} \equiv \beta V_{out}. \tag{2}$$

Constant β is an attenuation factor and is usually $\ll 1$. Working on resonance so that we can ignore the effects of the narrow-band filtering, let a voltage V_{in} be applied to the transmitter. Let us also subsume the effects of the probe tuning and matching network into the transmitter gain. If the transmitter then has an effective gain of α, it applies a voltage $V_{out} = \alpha V_{in}$ to the coil resistance R_c via source resistance R_t. Meanwhile, coupling from the second coil induces a voltage V_{12} of arbitrary amplitude and phase in series with the transmitter voltage. (For simplicity, we ignore the details of the source impedance associated with V_{12}.) The current that flows is then

$$i_p = \frac{\alpha V_{in} + V_{12}}{R_t + R_c}. \tag{3}$$

To apply the feedback at the same time as a pulse V_p, we let $V_{in} = V_p - V_s$. Substituting in Eq. (3) and using Eq. (2) we then have

$$i_p = \frac{\alpha(V_p - \gamma i_p) + V_{12}}{R_t + R_c}. \tag{4}$$

Solving for the current, we obtain

$$i_p = \frac{\alpha V_p + V_{12}}{(R_t + \alpha\gamma) + R_c} \rightarrow \left.\frac{V_p}{\gamma}\right|_{\alpha\rightarrow\infty}. \tag{5}$$

If $\alpha\gamma \gg R_t + R_c$ and $\alpha \gg V_{12}/V_p$, it is immediately clear from the equation that if the sample is changed, resulting in a change of R_c, or if the tuning and matching change slightly resulting in a change of gain α and R_t, there is negligible alteration in the current—it is constant at V_p/γ. The effective output impedance of the transmitter has been increased by $\alpha\gamma$, and the transmitter has essentially become a constant current source of transconductance $1/\gamma$. Now legitimately setting $\gamma = \beta(R_t + R_c)$ from Eq. (2), condition $\alpha\gamma \gg R_t + R_c$ becomes $\alpha\beta \gg 1$, the usual condition for feedback efficacy that the open-loop gain be large. In addition, Eq. (5) may be rewritten in the form

$$i_p = \frac{\alpha V_p + V_{12}}{(1 + \alpha\beta)(R_t + R_c)}, \tag{6}$$

which also highlights the condition. Setting $V_p = 0$ in Eq. (6), we see that the current induced by coupling is reduced by a factor $1 + \alpha\beta$, and remembering that current i_p then flows on account of voltage $V_{out} + V_{12}$ across resistance $R_t + R_c$, we obtain

$$V_{out} = -\frac{\alpha\beta V_{12}}{1 + \alpha\beta} \to -V_{12}|_{\alpha\to\infty}. \tag{7}$$

Current blocking is accomplished in practice by the transmitter's producing a voltage in series with the coil almost equal but opposite to V_{12}.

3. Experimental

To test the validity of the above idea, we have at present only one 128 MHz feedback spectrometer, and so have had to tailor an experiment accordingly. Thus, the two-coil array of Fig. 2 was employed. The coils sat above a saline phantom, coil 1 being connected to the spectrometer transmitter while surface coil 2 was driven by a network analyser. Reactive decoupling was provided by a paddle. Two measures of current in coil 1 were also created by lightly tapping the voltages across two tuning capacitors with the aid of baluns. This method is preferable, in this instance, to the use of sense coils as the latter may also have a small voltage induced by the B_1 field from the other coil. (Alternatively, very weakly coupled, shielded miniature transformers may be used.) When individually sitting above a large spinal imaging saline phantom, both square coils were tuned and nominally matched to 50 Ω with the aid of half wavelength baluns at 126.6 MHz—a convenient frequency determined by available capacitors and within the tuning range of the spectrometer. Unloaded, the Q-factor of each coil was ~420; loaded the factors dramatically reduced to 16 and 15. One coil was slightly further from the phantom (7.2 mm) than the other (4.3 mm) so that the coils could be overlapped if desired. The coils were then brought together to the positions shown, and with the aid of the network analyser driving

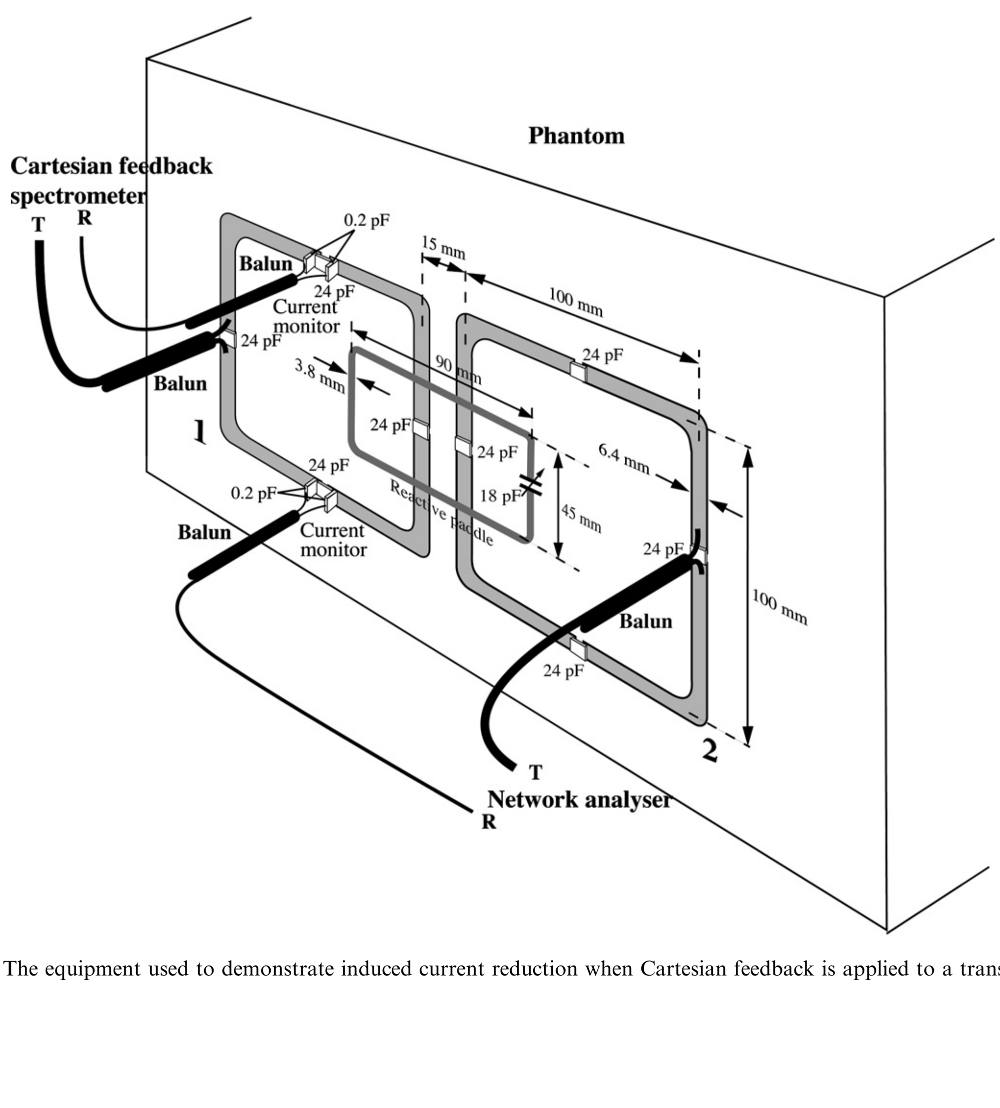

Fig. 2. The equipment used to demonstrate induced current reduction when Cartesian feedback is applied to a transmitter.

the second coil and temporarily receiving signal from the matched first coil (current monitors not yet used), the coil coupling was measured: it was −9.4 dB. The reactive coupling between the coils was now annulled with a tuned reactive paddle that resonated at 135.5 MHz with a *Q*-factor of 304 and a tuning capacitor of 7.5 pF. Thus the impedance of the paddle at 126.6 MHz was 0.6–21*j* Ω—not a particularly pure reactive condition, but adequate for our purposes. The coupling between the two coils' ports was, however, only reduced to −13.8 dB, showing that considerable resistive coupling remained, via the sample. The input impedance of each previously matched coil was found to have dropped by roughly 2 Ω.

With the network analyser still driving the second coil, the first coil was now connected to the quiescent but operational transmitter of the Cartesian feedback spectrometer. For the safety of the network analyser, lest anything should go wrong, a very low power (1 W maximum) amplifier of nominal output impedance 50 Ω was employed at the end of the transmitter chain. The first current tap was connected to the spectrometer's receiver, but with the feedback loop open for the moment. In other words, there was normal transmitter operation but with no voltage V_p applied to the transmitter modulator—the transmitter was merely functioning as a nominal 50 Ω load on the first coil's input. The second current-monitoring tap was attached to the receive port of the network analyser and a *relative* measure of the on-resonance-induced current flowing in the first coil was taken—it was −48.6 dB. From the values of the tap capacitors (0.2 pF), we might have expected −50.5 dB, corresponding to the previously measured −13.8 dB coupling, but both the values of the tapping capacitors and the output resistance of the spectrometer's transmitter were quite nominal. The spectrometer feedback, with 1 kHz filters and nominally 40 dB open-loop gain, was now turned on. The reduction in the current in the first coil was dramatic (−40.4 dB), as shown in Fig. 3A, and is in reasonable agreement with the following simplistic theory. In Eq. (6), setting $V_p = 0$, we let the gain α vary as

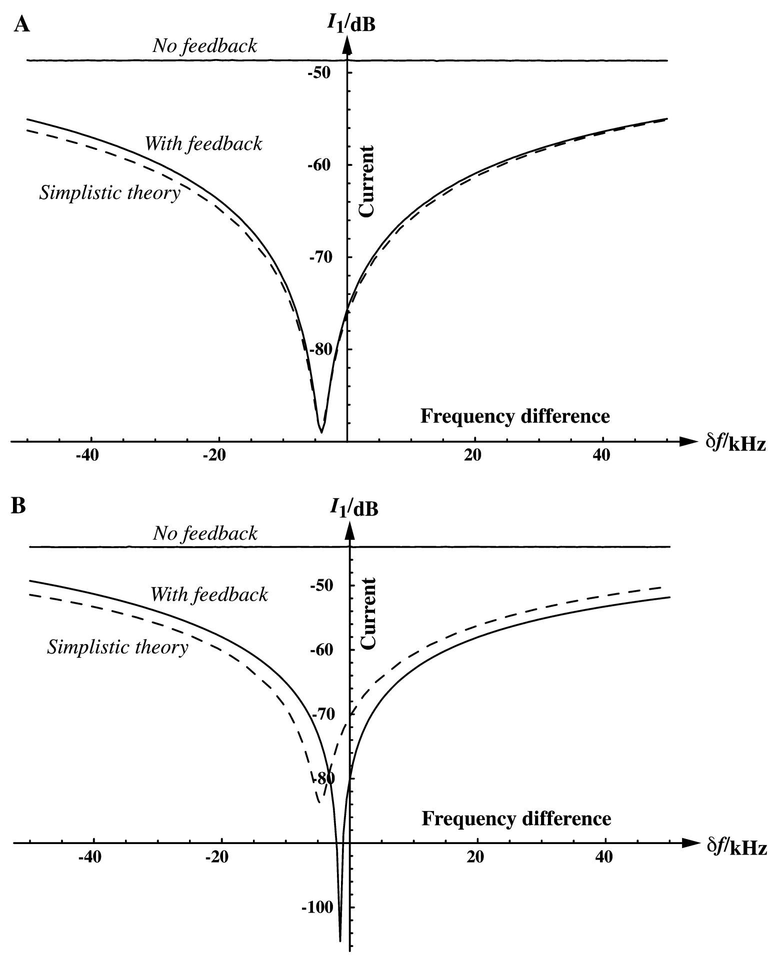

Fig. 3. The reduction of current in coil 1 of Fig. 2 by Cartesian feedback. In (A), reactive coupling between the two coils was cancelled with the aid of a paddle. In (B), the paddle was removed—note the considerable change of the current spectrum away from the theoretical curve. The spectrometer's and the network analyser's frequency sources disagreed by 4.6 kHz (36 ppm), hence the plots' shifts to the left.

$$\alpha = \frac{\alpha_0}{1 + j\delta\omega/\omega_c}, \tag{8}$$

where α_0 is the open-loop on-resonance gain (100), $\delta\omega$ is the distance off-resonance, positive or negative, and ω_c is the filter cut-off frequency (1 kHz) of the spectrometer [14]. We then have

$$i_p = \frac{V_{12}(1 + j\delta\omega/\omega_c)}{(1 + j\delta\omega/\omega_c + \alpha_0\beta)(R_t + R_c)}. \tag{9}$$

It is the absolute value of this function that is plotted in Fig. 3A, but so long as the imaginary component of the denominator is negligible, Eq. (9) may be rewritten

$$i_p \cong i_0(1 + j\delta\omega/\omega_c), \tag{10}$$

where i_0 is the current on resonance. As expected, the current increases off-resonance as the open-loop gain of the spectrometer is reduced by the filters.

The experiment was now repeated with the decoupling paddle removed so that there was reactive as well as resistive coupling between the coils. The induced current, not surprisingly, increased in the absence of feedback from −48.6 (Fig. 3A) to −44.0 dB (Fig. 3B), but in the *presence* of feedback, it is the change in the shape of the response that is noteworthy—it shifts and dips. There is no simple explanation and the phenomenon can only be explained with a full simulation that includes the source impedance of the coupling voltage V_{12}. The basic efficacy of the technique, however, remains the same and importantly, there is no sign of current "peaking"—a prelude to possible oscillation.

The experiment was performed once again with the paddle of Fig. 2 removed and the mutual induction between coils now being cancelled by overlapping [1]. The results are shown in Fig. 4. In (A), the overlap was pre-adjusted for zero mutually inductive coupling between coils in the *absence* of the phantom, a common practice. However, the data were obtained in the *presence* of the phantom. The shift and depression of the experimental feedback current from the theoretical curve (cf. Fig. 3B) indicate that reactive coupling was still present, presumably contributed by the sample. In (B), the coupling was minimised *in the presence of the sample* by

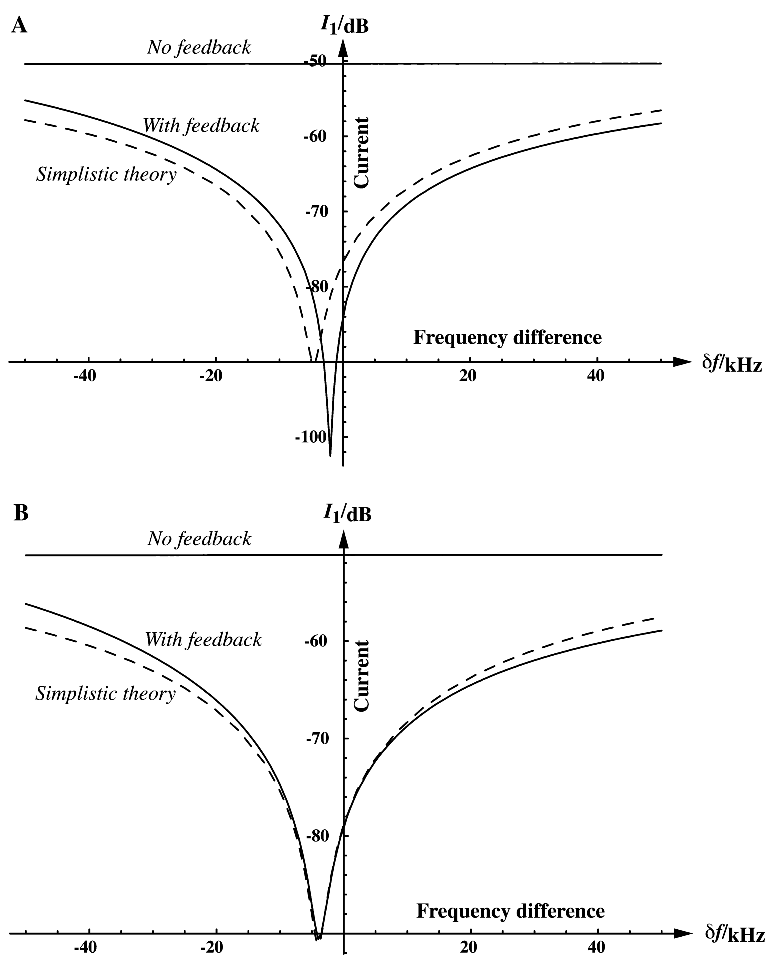

Fig. 4. The reduction of current in coil 1 by Cartesian feedback when the two coils are overlapped. In (A), the overlap was pre-adjusted for zero mutually inductive coupling between coils in the *absence* of the phantom. In (B), the coupling was minimised *in the presence of the sample* by optimising the overlap of the coils.

optimising the overlap of the coils. This presumably removed all reactive coupling and resulted in a current curve that at least close to resonance, matches the theoretical curve. These results highlight the fact that as well as resistive coupling, the sample contributes appreciable reactive coupling that should be removed. To that end, reactive coupling should always be minimised with the sample in place.

A point of concern, if a similar transmitter were attached to the second coil and turned fully on, was whether the transmitter on the first coil would have to try and exceed its maximum output voltage rating to do the job of opposing the induced voltage. It may be shown that the overload criterion for a coil-pair with matched transmitters is $|k_{12}| < 2/Q$, where k_{12} is the effective complex coupling factor between the two coils. We therefore measured k_{12} for the arrangement of Fig. 2 and found it to be $-0.0068 + 0.072j$. With a Q-factor of 16, the criterion was just met; however, with cancellation of reactive coupling it was easily met, and as the real part of k_{12} and $1/Q$ ride hand in hand, we would expect this generally to be so. With multiple coils, depending on their orientations relative to the first coil, the criterion may need to be tightened somewhat. In this regard, it is worth remembering that in extremis, a mismatch of the transmitters, as described above, is still available to provide assistance, as is resistive decoupling at the expense of some power and signal-to-noise ratio.

4. Conclusion

These experiments demonstrate that it is possible using Cartesian feedback to drive normally and efficiently a tuned, matched, and heavily sample-loaded coil in the presence of another similarly endowed coupled coil in close proximity. Cartesian feedback applied to the transmitter attached to the latter coil effectively introduces a high resistance in series with that coil, which inhibits current from flowing and prevents a back-EMF from being induced in the driving coil—the crosstalk is blocked. For optimal use, any large reactive coupling between coils should first be annulled with one of the various bridge methods available. The obvious inference is that the technique can make a multi-transmit phased array practical, each element being driven from its own Cartesian feedback instrument. It is stressed that no extra transmitter power is needed to produce a given B_1 field when feedback is invoked. This, in turn, opens the door to all the projected advantages of array coils for transmission—localisation of B_1 fields, control of SAR, production of B_1 fields having a specific spatial variation, and the creation of homogeneous B_1 fields at high frequencies over those surfaces where it is theoretically possible.

While we have concentrated on transmission, it must be emphasised that similar effects hold for signal reception, and Cartesian feedback can generally provide better decoupling with no loss of S/N than can preamplifier damping, though over a smaller bandwidth. Further, there is no reason why both techniques should not be employed simultaneously. The Cartesian feedback technique is neither simple nor cheap, but the cost of multiple transmitters is offset by the fact that individual power amplifiers need to generate much less power than a single main unit, and so are concomitantly less expensive than the latter. The total expense is then about the same. While the available blocking bandwidth (2 kHz) with an open-loop gain of 100 is comparable to that of a typical selective pulse, we are, nevertheless, actively researching negative group delay techniques [15] to increase it, and also hope to progress to the construction of eight instruments for a full phased-array test.

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