Diffraction-limited focusing of borehole radar arrays after Target-assisted hole trajectory correction.

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***Abstract* – Cusps and caustics were observed on HF-VHF borehole radar profiles, shot over 112 m across curved mine haulages cut in the norite footwall of a platinum reef. Interactive forward modeling and coherent imaging allowed the velocity and borehole paths to be corrected with the precision needed to synthesize a wide aperture.**

***Keywords* – Borehole radar, cusps, caustics, coherent imaging, aperture, resolution.**

I. INTRODUCTION

Boreholes are drilled underground to detect and map geological features that might have a bearing on mine safety and efficiency. The rocks through which they are drilled are translucent at VHF in many hard rock mines. The holes can serve as platforms from which to launch borehole synthetic aperture radar surveys. The precision with which the positions of the elements in any synthetic array are known determines its coherence aperture and bears directly on the resolution and the accuracy of any SAR-focused image.

Boreholes bend. Their trajectories are difficult to determine with the tenth-wavelength accuracy needed to achieve wide aperture diffraction-limited imaging in a VHF borehole radar survey. Borehole gyros are expensive, and they drift. Borehole compasses are affected by small deposits of magnetite or ilmenite. Magnetic declination wanders during magnetic storms. These factors clutter trajectory estimates made even with accurately calibrated 3D compasses..

Satellite-borne synthetic aperture radars are calibrated using reference reflectors on the ground [1] [2]. 3D seismic surveyors have imaged borehole geophones, to calibrate the drift space between the surface and a target resource [3]. Here, we use borehole radar reflections from curved mine tunnels, to characterize the space surrounding a master borehole. We then perturb a secondary hole's trajectory iteratively, to broaden its effective SAR imaging aperture.

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II. METHOD

The borehole radar survey was conducted in an underground platinum mine on the Western Limb of the Bushveld Igneous Complex in South Africa. An outline of the study area is shown in Figure 1. The area is encircled by horizontal haulages that form a loop ~125m in diameter. The UG2 platinum reef forms a sheet that dips due North at 11^{o} A dotted East-West line marks the intercept between-the planes of the reef and the haulage horizon. The haulages are all ~4m high, 3m wide. They contain metal rails, air ducts and water pipes, and power lines. They were cut for the most part in the ~30m thick slab of norite that separates the ~90cm thick, flat platinum-bearing UG2 chromitite reef from the underlying conformal UG1 chromitite layer.

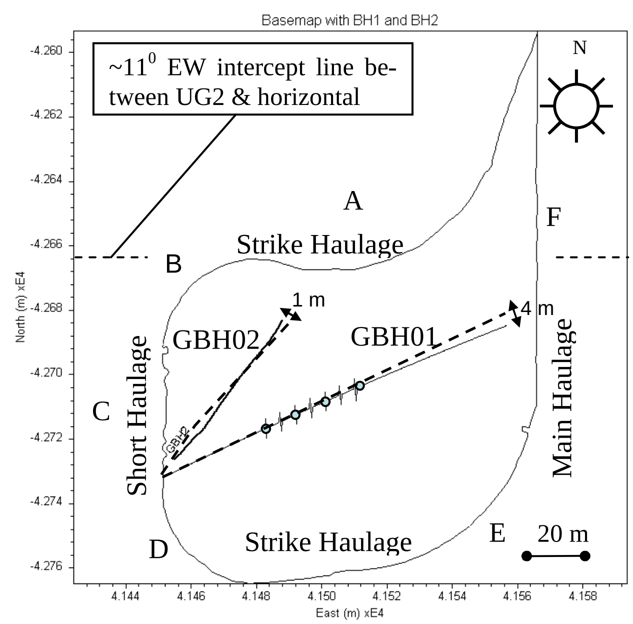

Figure 1. Basemap showing the initial (dashed) and corrected (solid) borehole trajectories and the mining tunnel; blue dots along GBH01 show the locations of fan data receivers.

Two 47 mm diameter (AX) boreholes GBH01 & GBH02 shown on the plan were both drilled from the eastern short haulage C. Their collars lie ~20 m vertically beneath the UG2 reef,. The longer hole –containing the ENE master array -- closed slowly on the dipping UG2 as it crossed the panel. The shorter hole – containing the NE secondary array -- dipped at ~10 ^{o} .in an attempt to maintain a constant distance between it and the UG2

Both holes were rotary-drilled with a screw-fed rig using AXT (47mm OD) drill bits. Holes of this type tend to curve upwards and to the right, in the direction of drill bit spin. They can deviate surprisingly abruptly if they cross faults at shallow angles. Principal faults in the area run North-South.

An electronic multi-shot (EMS) digital compass was run into each borehole in order to determine their trajectories with an estimated azimuthal accuracy of 2.5^{o} or +/- 5 m in 100 m, i.e. to within 1 radar wavelength at the bottom of the band 10 MHz and to within 10 radar wavelengths at the top of the band (100MHz). A systematic error of this order would cause a substantial radar squint.

A fixed offset (4.5 m) bistatic VHF borehole radar was run on a non-conducting pulley line at 10 m/min down and up GBH01, to form a synthetic aperture with a span of ~110 m. Next the transmitter and receiver were separated. The transmitter was pulled four times up and down a length of 60m in GBH02. The receiver was fixed in GBH01 successively at 36 m, 45 m, 55 m and 66 m from its collar.

The transmitter fired a train of -400V steps at ~11 kHz PRF into a broadband (10-125 MHz) 1.75m long dipole. One dipole arm was resistively loaded; the other housed the electronics. In a similarly housed synchronous receiver, echoes were amplified, and fed to a 250 MS/s 8 bit analog-to-digital converter (ADC). Stacking raised the dynamic range of the bistatic radar system to 11-12 bits (70 dB).

III. CALIBRATION OF MASTER ARRAY IN GBH01

A model borehole radar profile of GBH01 is compared to the profile that was actually measured in the field in Figure 2. The field profile was pre-filtered and gain-swept prior to its display. The model profile was synthesized by superposing scalar arrivals from closely spaced Huygens secondary sources on model tunnels, for each position of the bistatic borehole transceiver.

Obliquity factors and radiation polar patterns were built into the synthesis. The norite was assumed to be homogeneous, isotropic and loss-free. Straight haulages F and C, along which moveout is most rapid, give faint events on both model and field time sections because they lie close to the axial radiation nulls of the bistatic radar's dipoles.

Letters A-F tie arrivals on both time sections in Fig. 2 to the actual tunnels surrounding GBH01 in Fig 1. Tunnel curvature makes an important contribution to geometrical spreading. The strong caustic at [60m, 1.0µs] arises because GBH01 closes on the center of curvature of the arcing tunnel at E in Fig 1..

The move-outs of model and field arrivals were matched interactively by varying velocity, time offset, and the position of the end of the model borehole GBH01. A best-fit match was secured by using a velocity V=112.5 m/µs, a time offset To = 0.22 µs and by bending the tip of GBH01 4.1 m to the south.

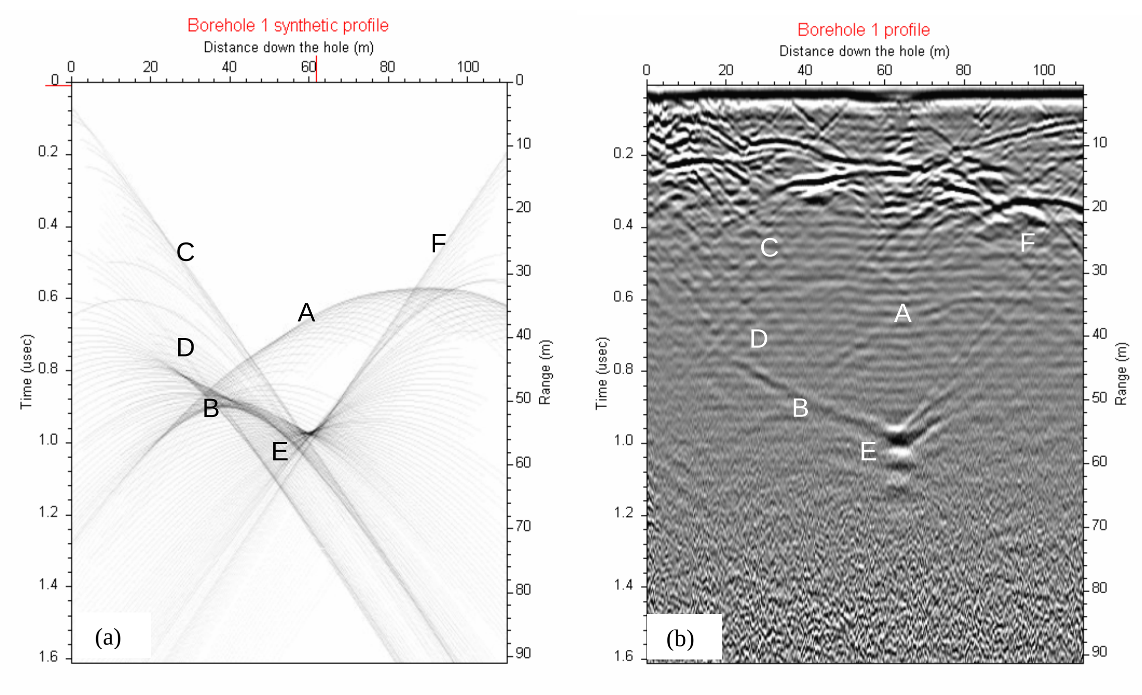

Figure 2. Profiles with synthesized (a) and real (b) reflections from different parts of the tunnel A-F shown on the basemap

IV. DIFFRACTION LIMITED IMAGING

A: Fan data acquisition and processing

Seven short vertical lines on the plan of GBH01 in Figure 1 mark axial distances from its collar at 5m intervals. Small circles at 36 m, 45 m, 55 m and 66 m represent stationary receivers, into which each of which so-called fans were shot using a transmitter that moved along GBH02.

Figure 3 shows a typical fan receiver gather. If the borehole were straight, and the velocity uniform, then the first arrival would be a perfect hyperbola. It almost is. However, deviation from a perfect hyperbolic shape can be seen in a slight lump at [16m, 0.2µs] and a wider amplitude depression centered at [35m, 0.2µs].

Borehole GBH02 was designed to maintain a fixed 10m elevation above underlying UG1, and a 20m depth below the overhanging UG2 chromitite reefs. Had these reefs been flat and parallel, the borehole straight and of fixed elevation then the secondary arrivals from first the UG1 and then the UG2 would have been hyperbolic. Both hyperbolae would have shared the same apex ordinate. In fact the UG1 appears to step, for its echo hyperbola splits in two. The UG2 appears to be flatter. Its echoes are closer to expectation. The UG2 arrival's asymmetry and apex shift suggests that GBH02 drifts rises slowly towards a dipping UG2.

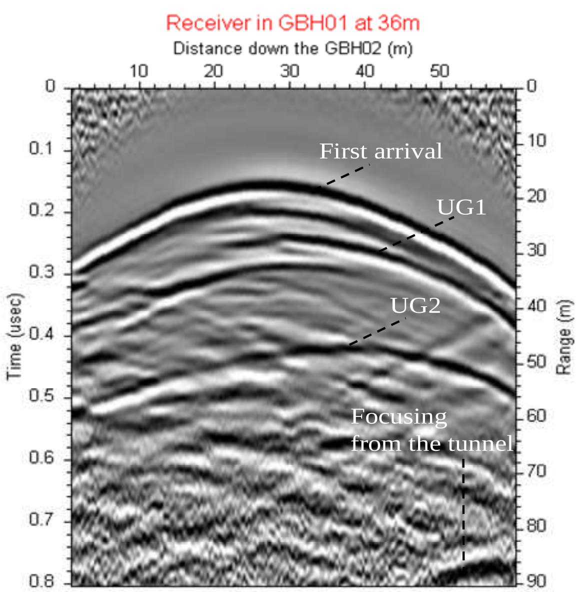

Figure 3. Fan receiver gather with main reflections identified.

The radar system's bandwidth and the shooting geometry allowed the reflected arrivals on fan gathers to be separated out and muted without influencing deviations from the perfect hyperbolic move out in the first arrival. These deviations are apparent in the muted gathers in Figure 4. Each exhibits a small but discernable kick (arrowed) when the transmitter in GBH02 is ~16m from the horehole's collar.

B: Migration & diffraction limited focusing.

Migration is also known as "SAR-focused imaging". Here it involves data translation from space-time of the sections in Fig. 4 to the plane that contains both boreholes. Velocity and time-zero offset were set at the V=112.5m/µs and To = 0.22 µs to match figures deduced from the cusp studies in Figure 2. The traces underlying Fig. 4 were Hilbert transformed and then migrated, perturbing GBH02 at each pass, in order to create the tightest possible images of the individual receivers at their known positions in GBH01.

The end-result is illustrated in Figure 5. Only with the "dog leg" shown in borehole GBH02 (see Fig. 1) was it possible to see four distinct receivers simultaneously off a transmitter baseline. The bend shown in GBH02, while small in magnetic survey terms, is consistent with drilling expectations. There is north-south faulting in the area.

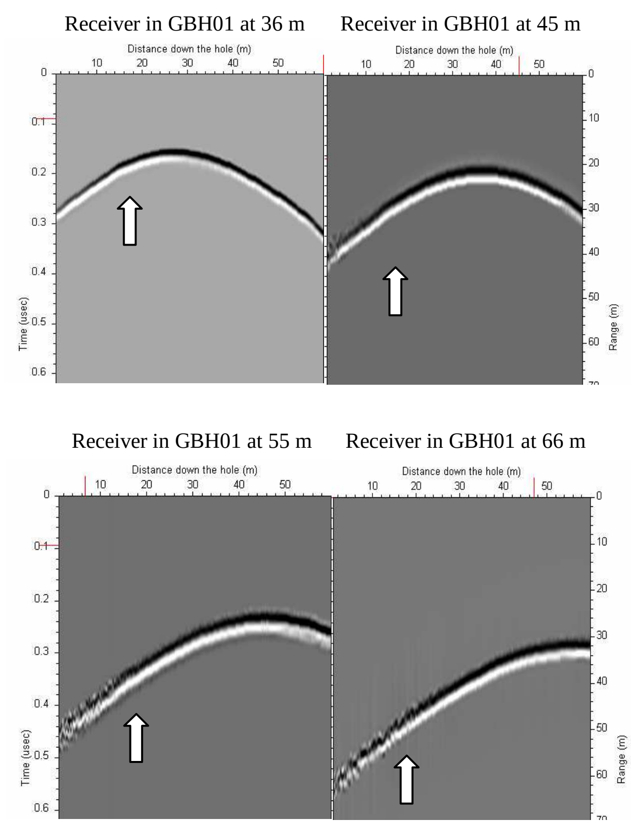

Figure 4. First arrivals of the four sets of fan data with receivers spaced at ~10 m intervals in GBH01

V. OBSERVATIONS

It is not hard to determine the relative axial positions of array elements in a 10-125MHz borehole radar array to better than 0.1 meters, or one-tenth of a wavelength at 100MHz. It is more difficult to determine their absolute positions, for boreholes can deviate abruptly. Drill strings with worn threads buckle under load. Rock layers and fault swarms may trap or deflect a drill bit.

Deviating GBH02 to the shape illustrated in Figures 1 and 5 doubled the synthetic array's resolving power. It halved the azimuthal width of the four images in Figure 5. After trajectory correction, the coherent aperture covered most of the borehole. The azimuthal width of main lobe varied from two meters for the image closest to bore-sight to eight meters for the farthest point image.

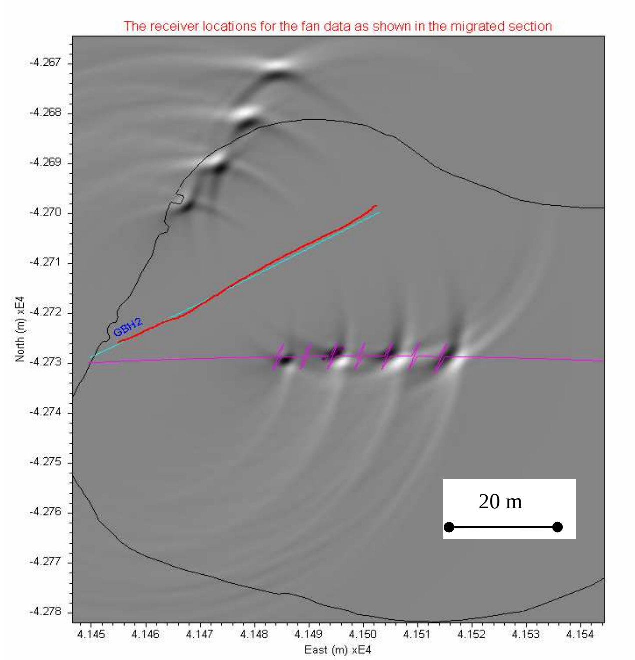

Figure 5. Migrated section created after correction of the trajectory of GBH02. Real images lie along the axis of GBH01

VI. CONCLUSIONS

Wide aperture diffraction limited focusing can be achieved if borehole trajectories are known accurately and if the velocity model is accurate enough to support chosen array apertures. If their sources can be mapped accurately then the cusps and caustics that develop on many mine time sections can be used both to calibrate host rock velocity, and to fix boreholes trajectories. Studies of point spread functions, shot between two boreholes, can, finally, be used to fix their relative trajectories to a degree that is sufficient to enable the coherent, interferometric imaging of reflectors.

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