

# A COMPARISON OF TECHNIQUES FOR PITCH / YAW COMPENSATION IN DEEP WATER MULTIBEAM SWATH ECHO-SOUNDERS

## ***Introduction***

One of the shortcomings of multibeam systems over the years has been their inability to provide 100% seafloor coverage in the presence of wave induced ship motion. Most recently, multibeam system manufacturers have begun to introduce new processes and techniques to compensate for these types of motion and to allow system users to begin to gain increased confidence in the quality and precision of the data they collect. This paper details the pros and cons of the various techniques being employed by these manufacturers, as well as the impact that these approaches may have on future multibeam developments, such as near real-time water column imaging and sea bottom characterization.

## ***Background***

Deep-water multibeam systems use low frequencies (typically 12 to 20 kHz) to sound to full ocean depths. At 12 kHz, a 1° beam width requires a transducer array length of approximately 8 meters. In addition to being a challenge to install on the hull of a vessel, these transducers are the highest cost part of the system. To minimize cost and complexity, a Mills Cross arrangement has been employed exclusively in deep water. While each array may have a 2-dimensional matrix of transducers, one dimension is much larger than the other. The projector array length parallel to the keel defines the along track resolution.

Early systems transmitted a single full swath ping each cycle, waiting for all echoes to return before launching the next ping. Transmission was normally compensated for pitch by steering the beam in the along track direction. This resulted in a conical beam pattern that ensonified a hyperbolic footprint on a flat sea floor.

In deep water, a vessel will typically move through more than a complete cycle of pitch and yaw between pings. This results in a series of along track footprints in which the curvatures and azimuths of successive pings are essentially uncorrelated. When pitch and/or yaw angles exceed the along track beam width of the projector array, gaps in sea floor coverage will occur in these systems unless the swath width is extremely narrow.

Pitch compensation is used to place the nadir beam directly below the vessel, resulting in equal beam spacing along the vessel track line. The commonly accepted definition of coverage in a Mills Cross system is the area between the half power points of the transmitted beam in the along track direction relative to its peak power at any given swath angle. Using this criterion, a 1° system (half power is 0.5° ahead and behind the swath line of peak power) surveying a 120° swath at 12 knots would just achieve 100% coverage along the track line. On either side, there is overlapping data in some areas and gaps in coverage in other areas. The earliest commercial systems surveyed only a 40° swath and had beamwidths in excess of 2° along track. For these systems, gaps in coverage were not an issue. As along track resolution has improved and swath widths have increased, the picture has changed dramatically.

The latest generation of deep-water systems use a variety of techniques to mitigate this condition, providing in some cases complete bottom coverage for worst case pitch and yaw conditions consistent with sea states in which survey operation is possible. There are two methods to improve coverage. One method is to stabilize the transmitted beam

across the entire swath. The other is to transmit multiple full swath pings per ping cycle to increase along track coverage each ping cycle.

To efficiently obtain the high source level necessary for full ocean depth performance, projector arrays are built from high-Q elements. The bandwidth of these projector elements is typically about  $\frac{1}{4}$  of the nominal operating frequency. It will be shown that utilizing this limited bandwidth effectively is key to all three current methods used to achieve full seafloor coverage.

### **Sector Scan**

The sector scan technique uses a 2-dimensional projector array which, in addition to forming a beam that is narrow in the along track direction, is capable of forming a beam that is somewhat narrow in the athwart ship direction as well. Its along track beamwidth is narrower than that athwart ship, so it is still much longer along keel than athwart ship.

By transmitting a rapid succession of pings, each steered to a different athwart ship angle, an entire swath is ensonified each ping cycle. Each of the successive pings ensonifies a sector of the entire swath, hence the name sector scan. Each sector, in addition to being steered in the athwart ship direction, is also steered in the along track direction to compensate for pitch and yaw. The peak power locus for a sector scanned swath resembles a cross section of a Fresnel lens.

The transmitted sectors actually overlap in the athwart ship dimension. Since each sector is transmitted at a slightly different time, accurate range resolution requires that the receiver be able to distinguish the desired sector echo from the echoes of the overlapping sector(s). Transmitting each sector at a different frequency accomplishes this.

The use of multiple frequencies places restrictions on the number of sectors that can be used. Any transmitted pulse requires some bandwidth. This is obviously true for modulated signals such as chirps, but even simple pulsed sinusoids require a bandwidth approximately equal to the reciprocal of the pulse length. Sectors must have center frequencies that differ by at least this amount.

When pulsed sinusoids are used, range resolution is inversely proportional to pulse length. Athwart ship spatial resolution is also improved with shorter pulses in two ways. In non-specular regions, interferometric processing resolves sampled athwart ship angle to the region ensonified by the transmit pulse at any given instant. This region gets larger proportional to the pulse length. Secondly, the non-specular region itself becomes larger as the pulse length shortens, allowing interferometric processing to be used effectively over a greater portion of the swath.

For these reasons, systems are operated using pulses as short as possible while maintaining adequate SNR to meet specified accuracy requirements. In the shallower regions of operation, short pulses, which require the greatest bandwidth, limit the number of sectors that can be transmitted by the high-Q projectors. Sector scanned systems typically use three sectors in shallow water and nine sectors in deep water.

If the pitch and yaw are uncorrelated ping to ping, three sectors will not guarantee complete coverage under all conditions in  $1^\circ$ , or even  $2^\circ$  systems. For a  $150^\circ$  swath and 8 second pitch and yaw periods, correlation breaks down at about 300 meters of depth. This forces a compromise between using long transmit pulses and risking incomplete coverage at high sea states.

## ***Swept Beam***

The swept beam technique uses a flat 2-dimensional projector array with its major axis parallel to the keel of the ship, similar to that used for sector scan. The array creates an elliptically shaped beam whose narrow axis defines the along track resolution. This beam is directed to one side of the swath initially by setting relative initial phases into the elements in the athwart ship direction. Phases along track are also set up initially for pitch and yaw correction at the edge of the swath.

To cause the beam to move across the swath, slightly different frequencies are set into each transducer. This causes the phase relationships among the transducers to change continually over time, causing the beam to change direction continuously from one side of the swath to the other. The larger the frequency differences, the faster the phase relationship changes. This corresponds to a shorter pulse. Even though each transducer is driven at a unique frequency, the combined effect in the beam direction is a single frequency that is the mean frequency of all transducers. By updating the frequencies during the ping the direction of beam movement is altered to compensate for pitch and yaw as the vessel moves during the transmission. The resulting swath footprints for a series of pings are essentially evenly spaced parallel lines except at the outer edges. The reason for the curvature at the outer edges is that the beam is swept only through about a 120° swath angle. Outside this region, the beam is held stationary at the beginning and end of transmission to ensonify the bottom out to  $\pm 75^\circ$ . The outer swath regions (between 60° and 75°) are therefore curved similar to the outer halves of the outer sectors in sector scan transmission.

The time required for full swath transmission depends on the width of the projector array; the wider the array, the narrower the beam in the athwart ship direction, and the slower it must sweep to create a particular pulse length. Transmission is typically accomplished within a time period of approximately 10 times the effective pulse length. Effective pulse length is the time required for the main lobe of the elliptical transmit beam to cross over a particular athwart ship angle. Thus a 2-ms. pulse requires about 20 ms. to transmit.

The bandwidth required to sweep a beam in the athwart ship direction with no pitch or yaw compensation is only slightly larger than that required to transmit a static ping of equivalent pulse length. A 2-millisecond pulse, for example, requires 500 Hz bandwidth for a static pulse. A swept beam with a 2-millisecond effective pulse length requires about 575 Hz, or 15% additional bandwidth. Pitch and yaw stabilization requires additional bandwidth. Worst case for both pitch and yaw of 10° is 2.9 kHz for a 1° beam and 2-millisecond pulse, which is within the capabilities of a 12 kHz projector. Thus the swept beam can provide complete yaw and pitch stabilization under all operating conditions. This is the only current technique that can provide this level of pitch / yaw stabilization at all pulse lengths.

The unique ability of the swept beam to perform with a high directivity index in shallow water with short pulses allows dynamic shallow water focusing of the transmitted beam. The range to a flat sea floor varies with athwart ship angle. Because the swept beam covers a narrow sector athwart ship at any instant, the beam can be focused for the mean range of the covered sector. This range can be varied continuously as the beam sweeps, using the depths from the previous ping to set the focus range across the swath. Simulations have indicated that 1° beam resolution can be maintained to 200-meter depth at 12 kHz.

### ***Multi-Ping***

Multi-ping is similar to sector scan in that a number of pings are launched in rapid succession at different frequencies each ping cycle. Instead of concentrating each ping into a limited athwart ship angular sector, however, multi-ping covers the entire swath with each ping. Each of the pings is compensated only for pitch; the array is treated as a one-dimensional entity. Each of the pings is steered to a different along track angle, typically overlapping in the along track dimension at the half power point at the nadir beam.

While this approach does not stabilize the transmitted beam for yaw, it nonetheless improves bottom coverage by increasing the along track area ensonified each ping by the number of pings launched. Bottom coverage is essentially the same as for a pitch compensated system with a wide along track beam. Along track resolution is higher than this footprint when the number of transmissions is more than one per ping cycle. In fact, if as many full swath pings are launched as sectors, coverage should be as good as sector scan. To achieve full coverage with  $10^\circ$  pitch and yaw, approximately nine pings would have to be launched per ping cycle with a  $1^\circ$  system.

Multi-ping suffers from the same bandwidth limitation that sector scan does. Thus, when using narrow pulses, the number of pings per cycle must be decreased. This reduces the effectiveness of the technique in shallow water.

A disadvantage of this technique is that, since each ping ensonifies the full swath, the directivity index is lower than with sector scan or swept beam. This translates to a lower source level. Of course, using a larger array could recover this lost source level, but this would drive up cost in what is already the most expensive part of the system.

An advantage of the multi-ping technique is potentially lower cost. Depending on the amount of source level sacrificed, the projector array can use fewer elements and therefore be less expensive to produce. Also, the number of individual power amplifiers is greatly reduced, although each amplifier must produce more power.

### ***Other Considerations***

Data collected by multibeam bathymetric systems is being used for more than bathymetry. Amplitudes are used for imagery (side scan) and for bottom backscatter evaluation to obtain bottom classification. Relative to conventional side scan systems, side scan from bathymetry is low in resolution, but has the advantage of being corrected for seafloor topography.

Conventional side scan systems are towed beneath the sea surface. This isolates the sonar from the effects of surface waves, and provides a stable platform where successive pings are quite parallel. Since bottom backscatter will vary with angle of incidence, image quality degrades when successive pings are not parallel, even with proper positioning relative to each other. The swept beam technique provides the closest approximation to this ideal condition, deviating only outside of  $60^\circ$  off center. The use of a single frequency for each full swath also makes it easier to generate high quality images, by removing the variation of absorption with frequency.

Bottom classification using backscatter amplitude is a less mature application than imagery. For this application, it may turn out that having data from a number of frequencies, as obtained from sector scan or multi-ping, is beneficial, analogous to a spectrum analyzer. The open question is whether the bandwidth is wide enough to provide a significant advantage over single frequency measurements.

To date, deep-water multibeam systems have all used simple pulsed sinusoidal transmission. As processing power increases, future systems will likely use modulated signals to increase SNR or to limit power levels to mitigate marine mammal disruption. In general, the use of modulated waveforms requires time delay beamforming techniques. While the sector scan and multi-ping transmissions are not restricted to using phase beamforming, and could therefore employ any modulated waveform, the swept beam approach, exclusively using linear FM (chirp) waveforms, would likely be a satisfactory transmission method used to deal with this situation.

### **Summary**

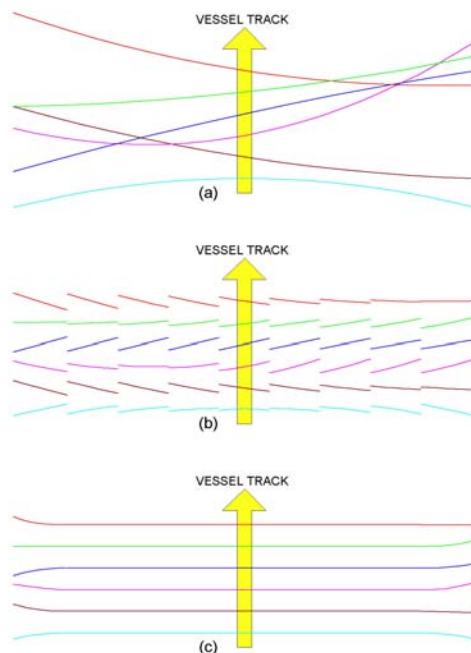
All three techniques are capable of providing complete bottom coverage in deep water. Only the swept beam affords complete coverage in shallow water at high sea states without compromising on pulse length. Swept beam and sector scan provide, in general, a higher source level and therefore improved deep water performance relative to multi-ping.

Swept beam offers the best shallow water focusing of the transmit beam. Sector scan is second in this ability, with multi-ping least able to provide focusing improvement. Swept beam provides the best ensonification for producing imagery, as all swaths are illuminated from a common direction at a single frequency.

As manufacturers incorporate signal modulation techniques to improve SNR and/or across track resolution, swept beam is limited to linear FM sweep (chirp) transmission. Sector scan and multi-ping can use other chirp profiles, as well as Barker codes or other modulation techniques as well as linear chirps.

The use of multiple frequencies by sector scan and multi-ping can provide narrow

Spectrographic backscatter data, whereas backscatter from swept beam is at a single frequency. It is unclear presently whether the multiple frequencies cover a broad enough spectrum to improve bottom classification relative to single frequency backscatter.



Peak power transmit beam footprints for six pings having uncorrelated pitch and yaw: (a) Multi-ping (one swath represents all pings, view as a single ping with wide along track footprint), (b) Sector Scan, (c) Swept Beam.



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