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ABSTRACT

The Yellowknife Seismic Array (YKA) has been an active part of Canada's contribution to nuclear explosion monitoring for more than 50 years. Near continuous seismic monitoring of the globe has occurred at YKA for the telltale signs of nuclear explosion testing since its inception in 1962, resulting in thousands of tests being identified. To achieve such a track record, the array has undergone several upgrades to its technology and infrastructure to meet the demands of the time. After nearly 25 years of service since its switch from analog to digital recording, YKA has again undergone a significant recapitalization of its infrastructure to modern standards of digital seismic monitoring to meet the demands of its mandate as the primary array station PS09 in the International Monitoring System and Canada's commitment and obligations under the Comprehensive Nuclear-Test-Ban Treaty. This report documents many of the changes made to the array during the upgrade through a data comparison by both the upgraded YKA and its predecessor collected simultaneously during the latter half of 2013. The comparison verifies the data quality of the new array, its readiness for inclusion into full operational status, and outlines recommendations for minor improvements prior to its recertification and the decommissioning of the former YKA.

Yellowknife Seismic Array History

The first series of negotiations in Geneva on a comprehensive ban on nuclear explosion testing among the then nuclear weapon states (U.S.S.R., U.K., and U.S.A.) began in the late 1950s. Seismologists from a number of countries, including Canada, were included in the technical delegations of the 1958 "Conference of experts to study the methods of detecting violations of a possible agreement on the suspension of nuclear tests." The experts agreed that underground nuclear explosions in the range 1 to 5 kilotons could be detected and identified if seismograph facilities were established in approximately 170 land-based control posts (Conference of Experts, 1958). Although later studies would revise these recommendations, research on appropriate types of seismograph facilities began almost immediately.

The United Kingdom Atomic Energy Authority (UKAEA) experimented first with a small seismological array installed at Pole Mountain in Wyoming, U.S.A., and demonstrated that seismic waves from nuclear explosions at distances around 3,000 – 10,000 km could be relatively efficiently detected. Computer processing of the recorded data allows the array to be steered like an antenna, not only to enhance detection of weak seismic signals but also to estimate independently the locations from which they came. With this experience, the UKAEA focused its research attention on this far-distance (teleseismic) range and re-designed its arrays to have approximately 20 seismometers spread over a region of ~25 km diameter. Four such arrays were installed; one in Scotland, Canada, Australia and India in the early 1960s and these remain in operation today.

The beginnings of the Yellowknife seismic array (YKA) began in April 1962 when the British Ministry of Defence approached the Canadian Defence Research Board about the possibility of locating a seismic array in Canada. An agreement was reached whereby the United Kingdom would supply and install all equipment and Canada would provide the site, do the necessary construction and, through the Department of Mines and Technical Surveys (now Natural Resources Canada), supply the personnel required to operate the array (Manchee and Somers, 1966).

The Yellowknife area was selected as the site for the array because of its location with respect to known nuclear test sites, its remoteness from coastlines, urban areas and other sources of cultural seismic noise, good communications facilities, and its location on the stable Canadian Shield. Installation was completed in late 1962.

The original YKA had 19 seismometer vaults in the form of a cross, with a distance of 2.5 km between individual vaults (Fig 1). The North-South line of instruments was designated as the “Blue Line”, while East-West was called the “Red Line”. This naming convention was followed by all four of the UKAEA arrays. Each seismometer was connected to the control centre by cables which supplied both power to the instrument vault and communication of the recorded data. The instrument output was used to modulate the amplitude of an audio tone that was transmitted along the cable to the control centre. In the control centre, the signals were recorded on 24-channel FM magnetic tape, with each reel holding 3 days of data. (Manchee and Somers, 1966)

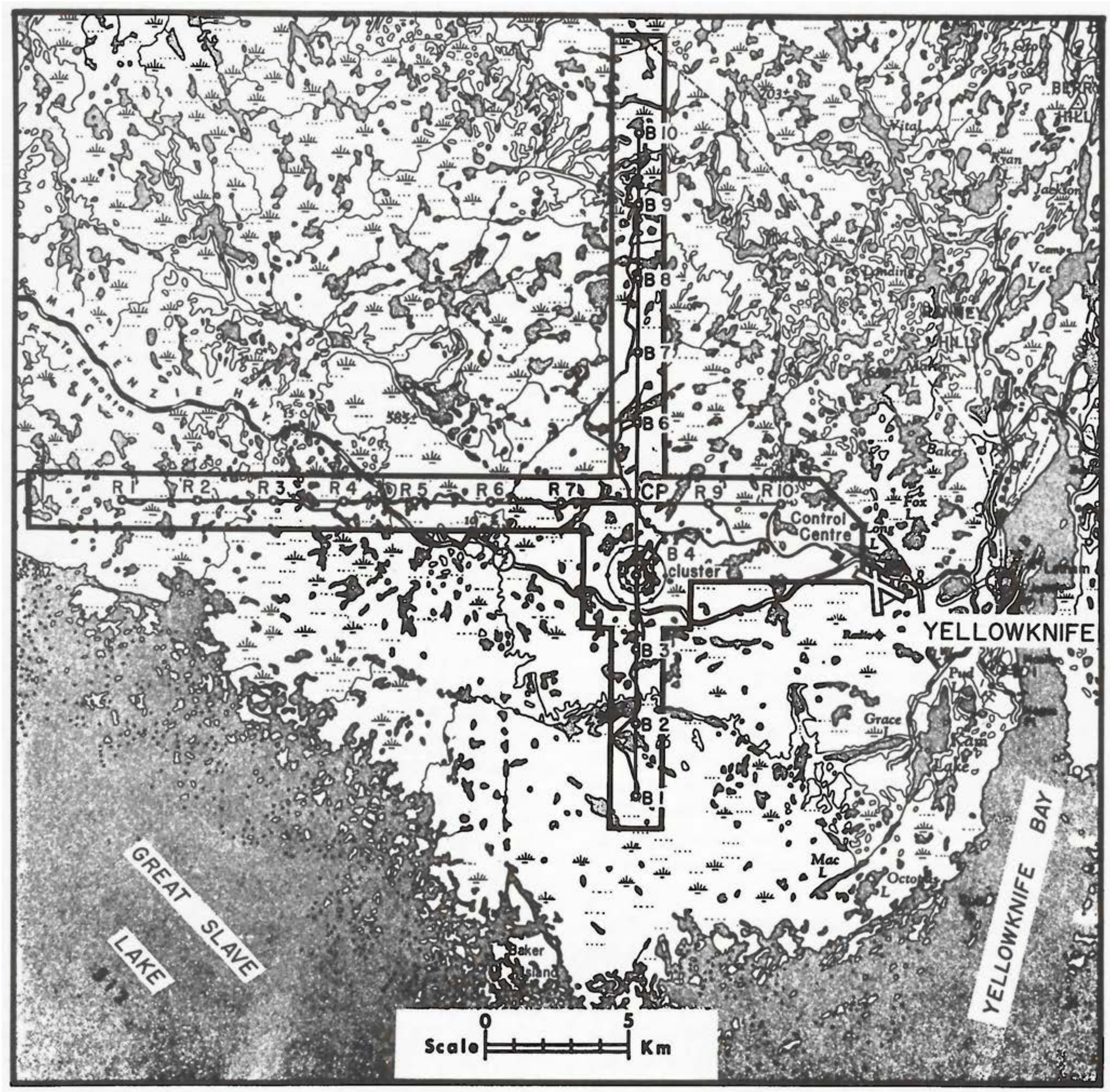


Fig 1. Layout and local property boundaries for the original Yellowknife seismic array (YKA). Station included 19 individual short period stations along two arms, spanning 25 km in length, and a small ~2 km aperture circular array. Reproduced from Manchee & Somers (1967).

A major problem encountered by the original array was cable maintenance. Severe lightning strikes and rodents chewing on the cables could cause enough cable breaks and equipment damage to put the array out of operation for several days. An initial solution was to elevate the cables and suspend them from wooden tripods, however, this exacerbated the lightning issues (Manchee and Hayman, 1972). Both problems were solved in 1971 by replacing the signal cables with VHF radio links between each vault and the control centre, and by installing a propane-fuelled thermo-electric power generator at each vault (Manchee and Hayman, 1972). At this time, three long period seismographs (Green stations) were added to the array to monitor for surface waves. Original plans called for five of these stations, however, only stations YKG1 – 3 were completed.

Various improvements in processing the seismic data from the FM tapes were made during the early years. However, a major breakthrough came in the early 1970s with the declining cost and increasing power of small computers. In 1974 the FM tape recording system was replaced entirely by an on-line computer which was programmed to automatically detect seismic signals, steer the array to locate the source of the signals, and store the data on digital tape (Weichert and Henger, 1974). The array operated in this configuration until a major refurbishing of the array was completed in mid-1989.

Throughout the 1980's, despite functioning effectively, increasing reliability problems began to occur in the analog systems of YKA. With the significant advances in seismometry, computers and communications it was decided that the array required a significant upgrade. In September 1985, the Secretary of State for External Affairs announced in a speech to the United Nations General Assembly that Canada, as part of its continuing contribution to the disarmament process, would upgrade its capability in seismic research and improve the array. The announcement was confirmed by a Cabinet decision in January 1986, to reallocate resources in order to carry out the modernization of the array over a period of three years. This decision allowed the array to be modernized to a completely digital system.

This major upgrade, completed in September 1989, included replacement of the older analog seismometers and FM communication systems, replacing them with modern short period and broadband instruments and 16-bit digitizers with broader and flatter frequency responses, providing less instrumental modification of the recorded ground motion signals. While the benefits of the thermal-electric-generators (TEGs) and radio-link communications were retained, many of the details and computers necessary for their operation were significantly upgraded, along with the control centre building necessary to house them. External communications to the Seismological Laboratory in Ottawa were also upgraded from primarily telephone line communications to satellite-based communications with the telephone as a back-up, and YKA has since run in this condition up to the present time.

With Canada's signing and eventual ratification of the Comprehensive Nuclear-Test-Ban-Treaty (CTBT) in December 1998, the Yellowknife array was officially accepted as one of Canada's primary contributions to the International Monitoring System (IMS) for monitoring States' compliance of with the CTBT. Designated as PS09, or Primary Seismic station #9, the seismological data collected by the array was one of the first to be incorporated into the newly formed IMS and was forwarded on to the Prototype Data Centre in Washington, DC in 1995 and later to the International Data Centre in Vienna for incorporation into their daily operations and analysis in late 2000.

By the mid 2000's, continuous operation of YKA had become troublesome as some of the array infrastructure began to show it's age. The instrument vaults, still 1960 vintage, had begun to corrode, leak and flood regularly. In winter, this water would freeze, encasing the instruments and digitizers in ice making them unserviceable until the spring thaw. Issues regarding TEG flame-outs were becoming more common in the winter as the propane became thick in the deep cold days of winter, requiring frequent service visits to keep sites running. While refuelling of the propane tanks, performed annually and requiring cold frozen conditions in order to allow Nodwell tracked vehicle (the only one able to carry propane to the sites), had become arduous as the aging vehicle required more frequent maintenance to deliver the fuel to all 22 station sites. Meanwhile, the rapidly evolving computer technology since the 1986-89 upgrades had made the computer systems obsolete. All of these issues made meeting the IMS standards for data uptime more and more difficult to achieve.

In late 2010, after more than twenty years of continuous operation since its last major upgrade, a proposal was presented to the Provisional Technical Secretariat of the CTBTO to once more significantly upgrade the aging Yellowknife array to current modern standards. This proposal includes replacement of the original corroding and leak-prone seismic vaults that house the instruments, replacement of the instrument digitizers to 24-bit technology, upgrade and replacement of the computer acquisition systems and radio communications, as well as, a major upgrade to the remote power systems from the TEGs to a hybrid solar-TEG system. This new array was constructed side-by-side to the old array, as the old YKA remained in continuous IMS operation; eliminating any monitoring downtime. These upgrades to YKA were completed by the end of 2012, marking the Yellowknife seismic array's 50th anniversary of continuous operation.

The benefit of the two arrays operating together allows a cross validation between the systems to ensure continuity of the high standards of data quality and the ability to compare modern observations of the new system to that of the old. The following report documents the changes made to the new Yellowknife seismic array and how its data compares to the observations of the old YKA.

2013 YKA Upgrade Summary

The design of the new Yellowknife seismic array has sought to maximize the efficiency and robustness of the numerous stations in the array to meet the rigorous IMS standards for data quality and uptime, while at the same time minimizing the number of onsite visits and amount of physical effort required by the onsite technicians.

The fine details of the complete upgrade is outlined in "Final Design for the Recapitalization of Primary Seismic Station PS09, YKA" (CTBTO, 2011), however, the following is a brief summary of the changes made.

Instrumentation:

The current instruments, installed during the 1986-89 upgrades for the Yellowknife seismic array, consist of two types of seismometers and digitizer pairings; one for the short period array elements and one for the broadband stations.

The primary short-period array utilizes Teledyne-Geotech S-13 seismometers (Fig 2a/b) with a natural frequency of 1 Hz at the 18 sites along the Red & Blue lines (R1-9, B1-B4, B6-B0), with vertical-only channels. These seismometers have been time tested and proven to be very robust, requiring no external power or specialized vault. Currently digitized with Nanometrics RD3 16-bit digitizers, they receive their time via a central clock at the Central Facilities Building (Control Centre) (CFB), which is telemetered via radio to the station from a specially modified GPS/GOES clock. Each short period station is sampled at 20 Hz (GSC, 1989).

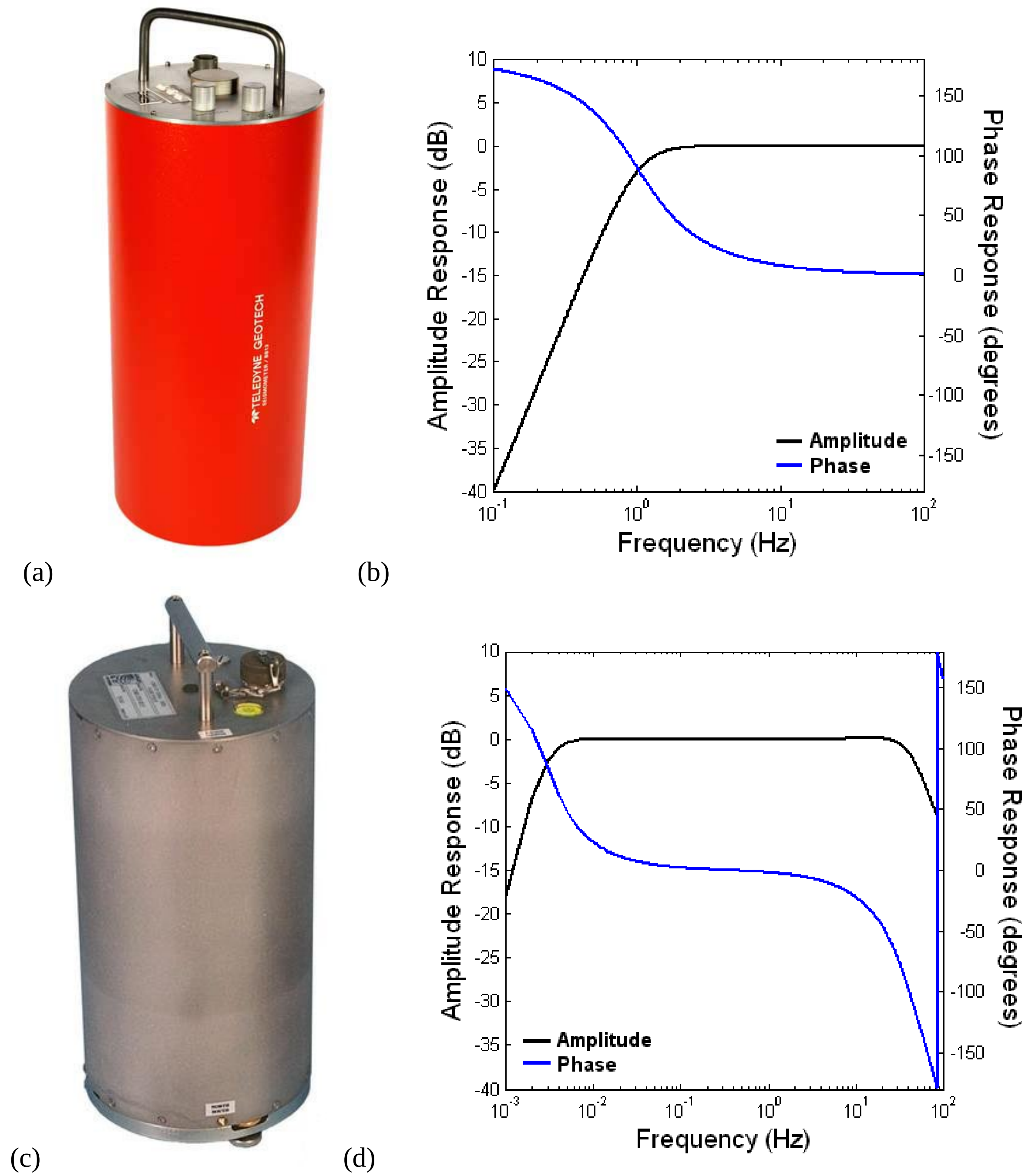
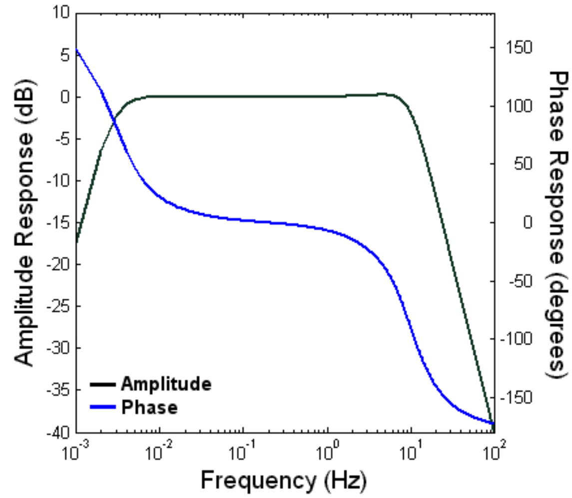
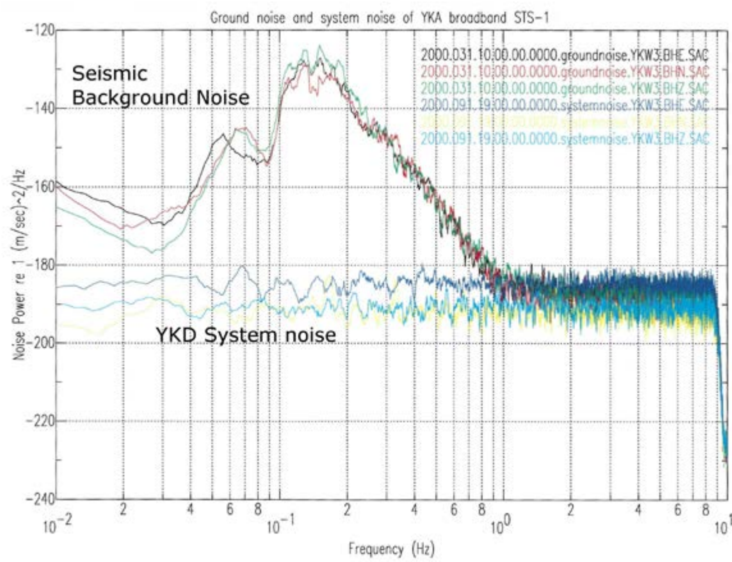


Fig. 2: Seismometers used in the re-capitalization of the Yellowknife seismic array. (a) The Teledyne-Geotech S-13 short period seismometer has been in use at YKA since 1989 and will continue to be used for the 25 km large aperture array. (b) Instrument response of the S-13 is sensitive to higher frequencies, with its natural period of 1 Hz. (c) The Guralp CMG-3T broadband seismometer replaces the earlier-era STS-1 at sites W1 and W3. (d) The CMG-3T has a very long period response out to 360 seconds, but also is sensitive to higher frequencies.

(a)



(b)



(c)

Fig. 3: Former broadband seismometer for Yellowknife seismic array. Installed during the 1986-89 upgrade, the Streckeisen STS-1 broadband seismometer (a) uses individual instruments for each of three components, one vertical and two horizontal, and are placed under partial vacuum to insulate and decouple the instruments from thermal and pressure induced noise. (b) Similar to the CMG-3T (Fig. 2c/d), the STS-1 has a long period response out to 360 seconds with superior self-noise characteristics, but has limited high frequency response above 10 Hz. (c) For YKA, STS-1 data are acquired by the YKD which has significant self-noise above ~1 Hz which limits the instrument to long period observations only (reproduced from Munro, 2000).

The broadband stations (YKW1-4) consist of three Streckeisen STS-1 broadband seismometers; one vertical, 2 horizontals (Fig 3a/b). Known for their exceptional performance at extremely long periods, these instruments are digitized at 20 Hz using a custom long period digitizer manufactured by the Geological Survey of Canada (GSC), which is hereafter referred to as the Yellowknife digitizer (YKD) (GSC, 1989). In addition, YKW3 also houses a three component set (1 vertical, 2 horizontals) of Teledyne-Geotech S-13 seismometers and RD3 digitizers. These instruments sample at 100 Hz and provide the high frequency coverage for the broadband instruments due to the YKD's internal noise being greater than the natural seismic background above ~1 Hz (Fig 3c). Like the short period stations, all these instruments receive their time from the telemetered central GPS/GOES clock at the CFB (GSC, 1989).

For the new 2011-2013 upgrade, it was decided that the instrumentation for the array was to remain as similar to that of the old design as possible in order to keep the instrument response comparable with that of its predecessors and facilitate easier comparison of signals recorded by the new and old systems in the future. Thus the Teledyne-Geotech S-13 was retained as the short period array seismometer of choice and 18 similar era S-13 seismometers as those currently operating at YKA were gathered and sent back to the manufacturer to be inspected, cleaned and re-calibrated specifically for the new YKA.

For the broadband stations it was determined that a new seismometer would be needed, as the current STS-1's did not meet the high frequency specifications of the IMS standards. Instead a new three component Guralp CMG-3T seismometer with a 360 second period cutoff would be installed at each broadband site (Fig. 2c/d). Most of the STS-1 seismometers and the high frequency short period instruments at YKW3 would be retired. Only one set of STS-1 seismometers would remain in operation for GSC historical continuity at one of the broadband stations, although not as part of the IMS PS09 array.

With planned upgrades to the array communications, new digitizers were required that would meet the high standards of the IMS. New Guralp CMG-DM24S3EAM digitizers (Fig 4) were selected for use at each of the new YKA short period and broadband stations. These digitizers contain onboard data authenticators (required by all IMS stations) and eliminate the current need for array data to be authenticated at the CFB for the new YKA. All RD3 and YKD digitizers will therefore be removed from service. In addition, sampling frequencies of all channels of the array, short period and broadband, would be increased from 20 Hz to 40 Hz with each regulated by its own independent GPS clock.

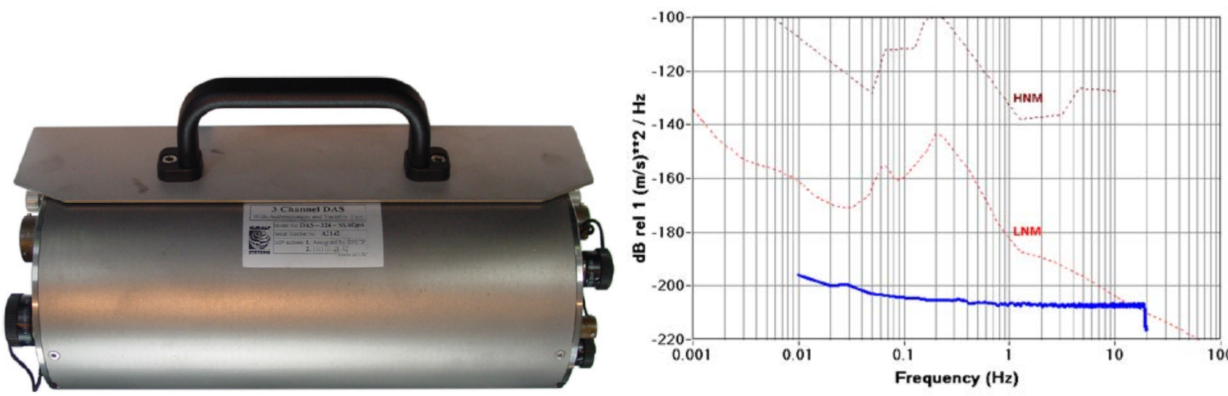


Fig. 4: The Guralp CMG-DM24S3EAM digitizer is the IMS preferred digitizer for the new YKA (left). This 24 bit digitizer replaces both the YKD and RD3 digitizers and includes onboard authentication and CD1.1 data output, required by all IMS stations. (right) Measured self-noise for the CMG-DM24S3EAM (gain setting of 2, using a reference sensitivity of 6000 V/(m/s)) is consistently below the seismic low noise background (Peterson, 1993).

With the new digitizers, instruments and sampling frequency, the new YKA's instrument response has changed slightly with the upper Nyquist frequency increasing to ~20 Hz and the short period response below 1 Hz becoming less attenuated without the additional low frequency poles introduced by the response of the RD3. The new and old instrument responses can be seen in Fig. 5.

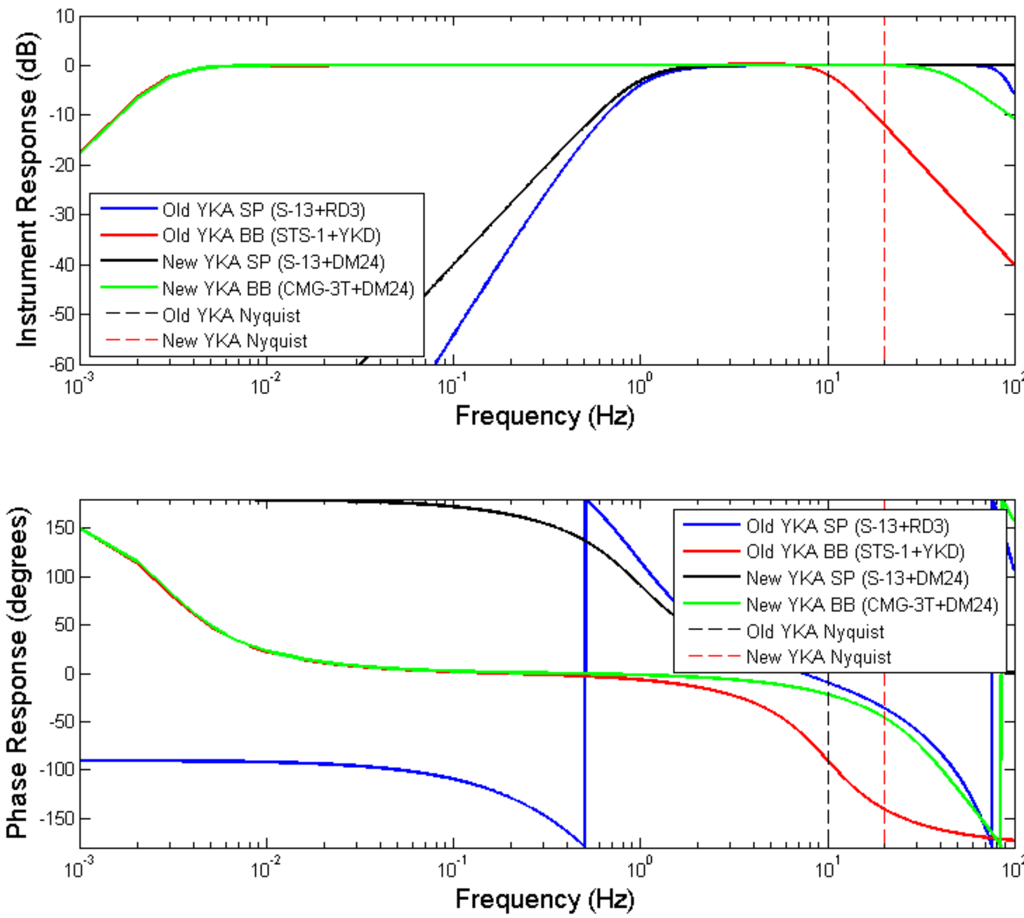


Fig. 5: Responses for the old Yellowknife short period (S-13/RD3 – blue) and broadband (STS-1/YKD – red) instruments versus the new Yellowknife short period (S-13/DM24 – black) and broadband (CMG-3T/DM24 – green) instruments.

Although the shape of the instrument response was modified, the overall sensitivity of the array was to remain the same. All efforts were made to increase the sensitivity of the new instruments to match that of the old system. For the broadband instruments, this simply required a special increase in the sensitivity of the CMG-3T's to 2 x 3000 V/m/s. For the S-13's however, with fixed sensitivities, a specially designed, low noise pre-amplifier (CMG-ELP-0110) was designed and manufactured for the S-13. Each amplifier, while similar in construction, was customized for each S-13 seismometer by matching the specific damping resistance of the pre-amplifier to the seismometer. Thus the pre-amplifier/seismometer became a matched set. With the pre-amp installed the sensitivity of the S-13 was increased by a factor of 40. Internal software settings within the CMG-DM24S3EAM digitizer then were set to match the sensitivity of the old array as closely as possible (Table 1).

Channel Name	Seismometer S/N	Seismometer Sensitivity (V/(m/s))	Preamp Gain	Seismo + Preamp Sensitivity (V/(m/s))	Digitizer S/N	Digitizer LSB (µV/Count)	Digitizer Frontend Gain	Digitizer Sensitivity (Counts/V)	System Velocity Sensitivity (Counts/(m/s))
YKAR1.SHZ	1192	386.05	40	15442.01	A3079	2.867	2	697593.30	10772240380
YKAR2.SHZ	832	401.43	40	16057.08	A3076	2.867	2	697593.30	11201309674
YKAR3.SHZ	822	386.02	40	15440.91	A3073	2.867	2	697593.30	10771478400
YKAR4.SHZ	2474	400.42	40	16016.86	A3081	2.864	2	698324.02	11184958772
YKAR5.SHZ	2349	382.43	40	15297.10	A3077	2.869	2	697107.01	10663717701
YKAR6.SHZ	2350	388.16	40	15526.24	A3038	2.875	2	695652.17	10800863787
YKAR7.SHZ	2911	393.64	40	15745.70	A3075	2.869	2	697107.01	10976439450
YKAR8.SHZ	1466	367.17	40	14686.70	A2165	2.865	2	698080.28	10252496657
YKAR9.SHZ	954	378.72	40	15148.91	A3088	2.868	2	697350.07	10564095713
YKAB1.SHZ	2338	372.98	40	14919.37	A3085	2.870	2	696864.11	10396776666
YKAB2.SHZ	2342	378.10	40	15123.93	A3087	2.870	2	696864.11	10539327225
YKAB3.SHZ	2343	371.19	40	14847.70	A3080	2.870	2	696864.11	10346828562
YKAB4.SHZ	2344	372.69	40	14907.68	A3083	2.867	2	697593.30	10399496461
YKAB6.SHZ	2345	388.78	40	15551.03	A3036	2.869	2	697107.01	10840730537
YKAB7.SHZ	2347	401.05	40	16041.93	A3086	2.869	2	697107.01	11182942418
YKAB8.SHZ	2493	389.05	40	15562.14	A3028	2.865	2	698080.28	10863626120
YKAB9.SHZ	2348	367.41	40	14696.44	A3072	2.865	2	698080.28	10259293780
YKAB0.SHZ	2340	383.51	40	15340.54	A3078	2.866	2	697836.71	10705195121
YKAW1.BHZ	T36859	5934.00	---	5934.00	A3041	2.868	2	697350.07	4138075314
YKAW1.BHN	T36859	5972.00	---	5972.00	A3041	2.867	2	697593.30	4166027206
YKAW1.BHE	T36859	5890.00	---	5890.00	A3041	2.870	2	696864.11	4104529617
YKAW3.BHZ	T36820	5950.00	---	5950.00	A3035	2.864	2	698324.02	4155027933
YKAW3.BHN	T36820	5944.00	---	5944.00	A3035	2.865	2	698080.28	4149389180
YKAW3.BHE	T36820	5956.00	---	5956.00	A3035	2.868	2	697350.07	4153417015

Table 1: Sensitivity settings for the new Yellowknife seismic array short period and broadband instrumentation.

Array Configuration:

The configuration of the Yellowknife seismic array has remained mostly unchanged since its construction in 1962. Originally consisting of 19 vertical, short period stations spaced ~2.5 km apart on two 25 km long lines oriented North-South (Blue Line) and East-West (Red Line), the two lines intersect each other to form a cross (Fig. 1). Of this original configuration, only one station of the 19 is no longer in operation, that of the eastern-most station, YKR0, closed in July of 1976 due to excessive noise caused by nearby gold mining operations and urban noise nearby the City of Yellowknife. The rest of the stations and overall configuration of the YKA short period stations has remained unchanged during all of its incarnations. This continues to be the decision, to keep the array in its original configuration so as to provide an unbroken dataset of now several thousand global nuclear explosion test observations from the same array for cross comparison to any future observations. Thus during the recent 2011-2013 refurbishment, no short period stations are to be closed or moved.

During the 1986-89 digital upgrade of the analog array, four new broadband stations were established, YKW1-4. These stations replaced the former analog long period instruments at YKG1-3. Of the broadband stations, currently only YKW3 remains in continuous operation as part of PS09. YKW1, 2 and 4 ceased operation between May 2008 and December 2009 due to ongoing power supply failures and digitizer breakdowns. In 2006 an additional non-IMS three component Guralp broadband sensor was installed at YKW1 for research purposes, sampling at 100 Hz. For the new YKA, it was decided that four broadband stations would not be necessary for IMS operations and only two of the broadband stations would remain. Thus YKW3 was as the primary site, due to its exceptional low noise characteristics and its current status as the operational broadband component for YKA. The broadband station at YKW1 would also remain as a backup with its benefit of having AC power to the instrument vault. Together the new YKA is not very dissimilar from its 1989 predecessor (Fig 6).

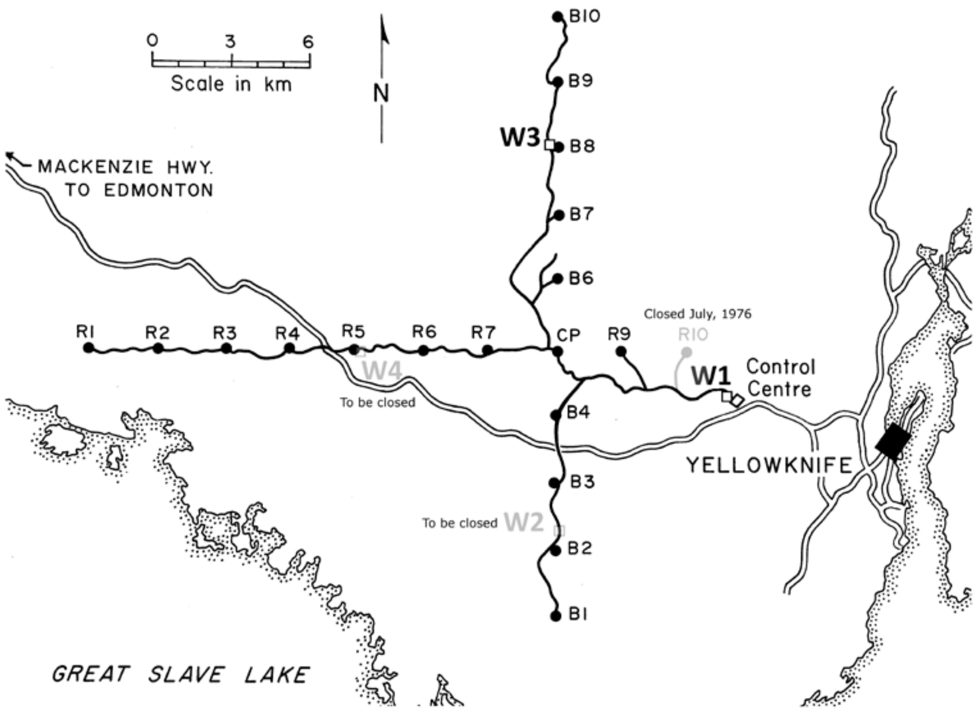


Fig. 6: Layout of the 2013 recapitalized Yellowknife seismic array. The complex consists of an eighteen (18) element short period array with two (2) broadband stations.

Vault Design:

The original 1962 short period vaults have generally remained in service even after the 1989 YKA upgrade. These vaults consist of two welded, steel half-cylinders 40 inches (1.016 m) wide set in concrete within pits that have been blasted out of the solid granite bedrock to a depth of 3 feet (0.9144 m). Steel convex lids, bolted to the drums and gasket-sealed, close the vaults off from easy access (Fig. 7, Manchee and Somers, 1966). These vaults have a history of leak issues and several have been abandoned at a few short period sites and moved due to flooding. These vaults have begun to corrode with age and continue to be prone to leaks and flooding. That in many cases these vaults are located in areas that are low lying, simply make matters worse, particularly during the spring melt.

Fig. 7: Image of the old and new short period vaults at YKAB6. The original vault consisted of two welded half-cylinders blasted into the bedrock, fixed in place with a concrete base and sealed with a convex lid (left). The new vault (right) is a two-stage surface vault consisting of a concrete base, with a sealed inner HDPE vault and outer insulated aluminum vault.

For the new YKA, it was decided that to avoid the issue of future flooding, new surface vaults would be constructed on top of the bedrock. These new vaults would be constructed within 10m of the old steel drum vaults to ensure signal coherency between new and old sites. In many cases, the new vaults are well within this limit and nearly side-by-side with the former vaults (Fig 7, Table 2).

Station Name	Latitude (°N)	Longitude (°W)	Elevation (km)	Distance from former vault (m)
YKAB1.SHZ	62.402336	114.606263	0.1464	0.87
YKAB2.SHZ	62.424675	114.606379	0.1518	2.25
YKAB3.SHZ	62.448491	114.606062	0.1595	2.55
YKAB4.SHZ	62.470925	114.605747	0.1648	2.34
YKAB6.SHZ	62.516409	114.605722	0.1746	1.10
YKAB7.SHZ	62.538932	114.606057	0.1779	2.39
YKAB8.SHZ	62.561431	114.605443	0.1715	8.77
YKAB9.SHZ	62.582921	114.604654	0.1883	3.43
YKAB0.SHZ	62.605918	114.606010	0.1961	3.15
YKAR1.SHZ	62.492827	114.944462	0.1421	1.21
YKAR2.SHZ	62.492806	114.895923	0.1462	1.87
YKAR3.SHZ	62.492924	114.847666	0.1476	2.64
YKAR4.SHZ	62.492656	114.799797	0.1501	1.58
YKAR5.SHZ	62.493142	114.750358	0.1553	2.77
YKAR6.SHZ	62.493157	114.701933	0.1621	3.32
YKAR7.SHZ	62.493205	114.654432	0.1685	2.07
YKAR8.SHZ	62.493084	114.606131	0.1679	2.89
YKAR9.SHZ	62.493042	114.556411	0.1726	2.59
YKAW1.BHZ/N/E	62.482203	114.484257	0.1707	No change
YKAW3.BHZ/N/E	62.561618	114.609925	0.1703	No change

Table 2: Geodetic coordinates for the new vaults of the Yellowknife seismic array and their separation from the former array vaults at each site.

The new surface short period vaults are schematically shown in Fig. 8. The vault consists of a thick concrete slab, chemically bonded atop a section of newly exposed and unweathered bedrock. Within the concrete a copper grounding mesh is imbedded and a round High Density Polyurethane (HDPE) pipe is immersed, again chemically bonded to the concrete to ensure a firm and leak-proof seal. This HDPE pipe is capped with a HDPE lid and forms the inner vault in which the seismometer is housed. A square outer aluminum vault is then constructed around this inner vault. The outer vault is bolted to the concrete slab, grounded to the copper mesh, sealed with a removable aluminum lid, and outfitted with an IMS required tamper switch. The cavity between the inner and outer vaults and lid is then filled with ~6 inches (0.1524 m) of extruded foam insulation. An additional float switch is included in the inner vault in the unlikely event of significant water penetration.

Broadband stations remain unchanged and in their original vaults, which consist of small manmade caves, blasted into the side of a bedrock exposure and sealed with insulated and steel cage doors, and outfitted with tamper switches. A poured concrete slab atop the bedrock inside the cavity serves as a pier for the emplacement of the seismometer (Fig. 4).

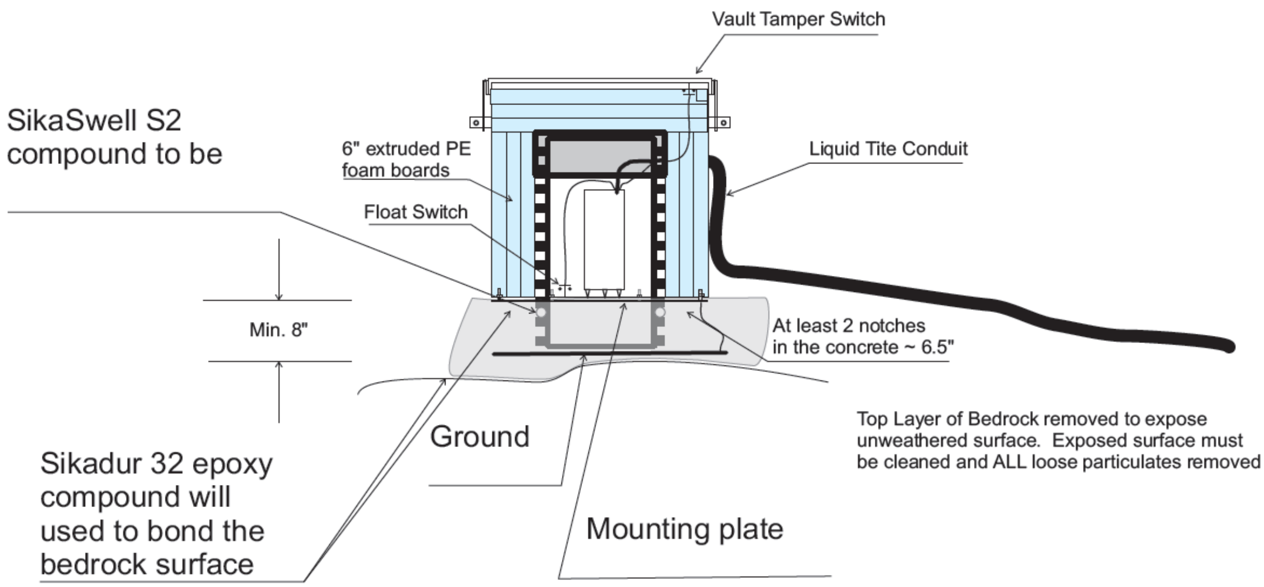


Fig. 8: Schematic diagram of the new Yellowknife short period vaults. The overall outer dimensions are 30” (76.2 cm) square, atop a minimum 8” (20.32cm) thick concrete slab. Inner vault is circular with a diameter of 37.5 cm.

Power Systems:

Since approximately 1971, remote station power at YKA has been supplied by Thermal Electric Generators or TEGs using liquid propane as a fuel. This method had proven to be generally more reliable and economical, although labour intensive during refueling. The power systems for the new YKA have been completely overhauled in an attempt to reduce the reliance on propane and TEGs for remote power and the frequency of costly propane refueling. The new power system relies primarily on a hybrid of solar recharged deep-cycle batteries with a TEG system used as a backup during cold winter months where sunlight to recharge the batteries is minimal or non-existent in Yellowknife.

The solar component of the new power system consists of six solar panels oriented towards South on a 25 foot (7.62 m) articulated tower (Fig. 9). Located between 30 – 40 m away from the seismic vault, the separation seeks to minimize the likelihood that seismic noise generated by the tower flexing or bending in the wind should contaminate the recorded seismic data (Edwards et al. 2012). Three banks of six deep cycle batteries are used to power the station throughout the spring, summer and fall seasons. During winter, when solar recharge is unavailable, the batteries slowly discharge. Battery voltage is routinely monitored remotely at the CFB and if voltages drop below an acceptable level at a station, the TEG is started to recharge the batteries and power the station through the remainder of the winter, until sufficient insolation is available in the spring.

Fig. 9: Hybrid Solar-TEG remote power system for the Yellowknife seismic array stations. Six solar panels are mounted upon a 25´ (7.62 m) articulated tower (left) and charge a bank of batteries (left of center) to power the station. A thermal electric generator (TEG, right of center) is used during later winter months when sunlight is unavailable, using propane (right) as its fuel source. The tower also provides a platform for the communications antenna.

As discussed, a new Thermal Electric Generator is used as a backup power source at all stations (Fig. 9). This TEG is connected in parallel with the solar array and utilizes a larger propane tank. The larger tank and back-up-only nature of the TEGs mean that costly and time consuming refueling is kept to a minimum, while ensuring station remains functional and data acquisition continues uninterrupted.

Site Communications:

Data communications from the elements of the Yellowknife array continue to be broadcast back to the Central Facilities Building via radio-link. The former 457 - 459 UHF radio system, however, has been upgraded to a new 2.4 GHz Wi-LAN system. Dish antennas located atop the articulated solar tower broadcast (Fig. 9) and relay both data and operator instructions to and from each remote site. Two radio subnets connect various sections of the array to specific stations (e.g. R5) acting as data relays (Fig 10). The relays then broadcast back all data to the CFB or retransmit instructions to the outer stations. Further work is being done to ensure redundancy within this radio architecture in case of subnet dropouts, although current completeness statistics show that the new system is working well.

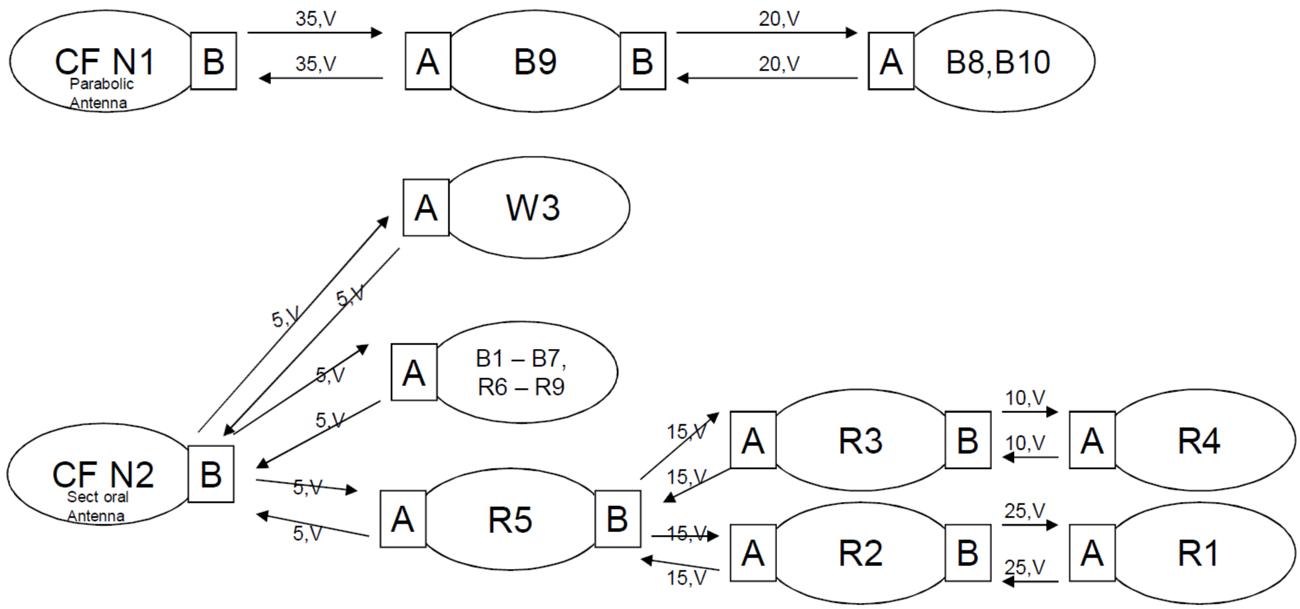


Fig. 10: Schematic diagram of the new Yellowknife seismic array Wi-LAN subnets to/from the Central facilities building.

Acquisition Systems:

With the installation of new digitizers and communications equipment at each array remote site the previous outdated data acquisition systems at the CFB have been replaced by updated computers and software. Data from each digitizer is broadcast and received in two data streams, Scream! and CD1.1. Scream! data allows the operators and technicians in Yellowknife to monitor and assess data quality and issues at the 20 remote array stations, while the CD1.1 data stream (with its mandatory authentication headers) is forwarded via a WAN internet connection to Ottawa for archiving and transmission to the International Data Centre in Vienna for treaty monitoring as part of the IMS. A secondary link to Ottawa will be setup to broadcast the data along a secondary route through an iDirect satellite link, however, this process will begin once the old YKA system is decommissioned due to current limitations of satellite bandwidth.

Seismic Noise Levels

The Yellowknife seismic array has been known for many decades as having very low levels of background seismicity. This is achieved primarily due to its remote location, stability of the Canadian Shield and distance from oceans and major urban centers. During the renewal of the array, assuring that these background seismicity levels remain consistent and free of artificial sources of noise was deemed paramount. As the majority of the infrastructure for the new YKA was to be replaced, except the short period sensors, re-evaluation of this background is required to assess both the theoretical instrument response and that the new infrastructure is performing as anticipated.

To evaluate the background noise at each element of the array, one hour segments of data were extracted from both new and old arrays each day from July to October, 2013 corresponding to local midnight, 6am, noon and 6pm or 00, 06, 12, and 18 MST (Mountain Standard Time) or 17, 23, 05 and 11 UTC. Each of these one hour segments were then subdivided into 5 or 30 minute windows for the short period and broadband channels respectively, with an overlap of 80%. For each of these data windows, a spectral power trace was computed and the resulting median spectra taken as representative of that hour, for that day. The median of each day over the approximate 90 days of data were then computed, resulting in the median spectra representative of the seismic background noise during local midnight, morning, noon and evening for each element of the array. Plotting these spectra atop each other provides a means of evaluating the changes in the background over the course of an average day (Fig 11).

It is observed that for frequencies below ~2 Hz, very little variability is seen over the course of the day as few diurnal sources produce noise at these frequencies (Fig 11). Above ~2 Hz, for nearly all stations, the background increases ~8 to 15 dB above midnight noise levels by noon. Mornings (6am) and evenings (6pm) are generally comparable in noise characteristics, and similar in structure, but slightly quieter than the noon hour background.

One feature of the seismic background includes a correspondence between the proximity of a station to the MacKenzie Highway and the noise levels above 10 Hz (Fig 11). At all times of day, the closer a station is to the highway, the greater the noise above ~10 Hz, thus stations R4, R5, B3 and B4 tend to have the highest seismic noise in the array above 10 Hz; where the highway crosses the red and blue lines. While one may anticipate higher levels of urban traffic along the highway, the relative increase in background at these frequencies is constant throughout the day, which suggests this is natural in origin. A working hypothesis is that this may be due to an increase in natural tree sway due to winds along the highway. As the MacKenzie highway runs predominately west-east, and the dominant winds are westerly, the highway may become a natural wind corridor, creating increased seismic background at higher frequencies as the local tree cover sways and couples into the ground through the roots. As distance increases from the highway, this effect decreases as wind is broken down by the more uniform tree cover.

A secondary, but consistent, spectral feature seen across the array is a broad, low amplitude peak at ~5 Hz. The source of this feature is unknown, however it seems to be artificial as it increases in power slightly at stations closer to the City of Yellowknife. Further investigation is needed to uncover the source of the peak.

Finally, to ensure that the background observed and theoretical response of the new YKA is consistent with the known response for the old YKA, a comparison is made to the same spectral data acquired with the former array (Fig 12). Inspection shows a very good correspondence between old and new arrays, with much of the spectra overlapping. In several cases, significant improvements in the noise at high frequencies is seen, such as at B0, B7, R1, R2, R3, and W3. This is likely due to the improved noise characteristics of the CMG DM24-S3AEM digitizers over their circa-1986 predecessors, the RD3 and YKD's. As well, the new array removes old problems, such as low frequency digital noise spikes (e.g. B3, R1 and R3) and slow drifting of the seismometer's natural frequency (e.g. B8).

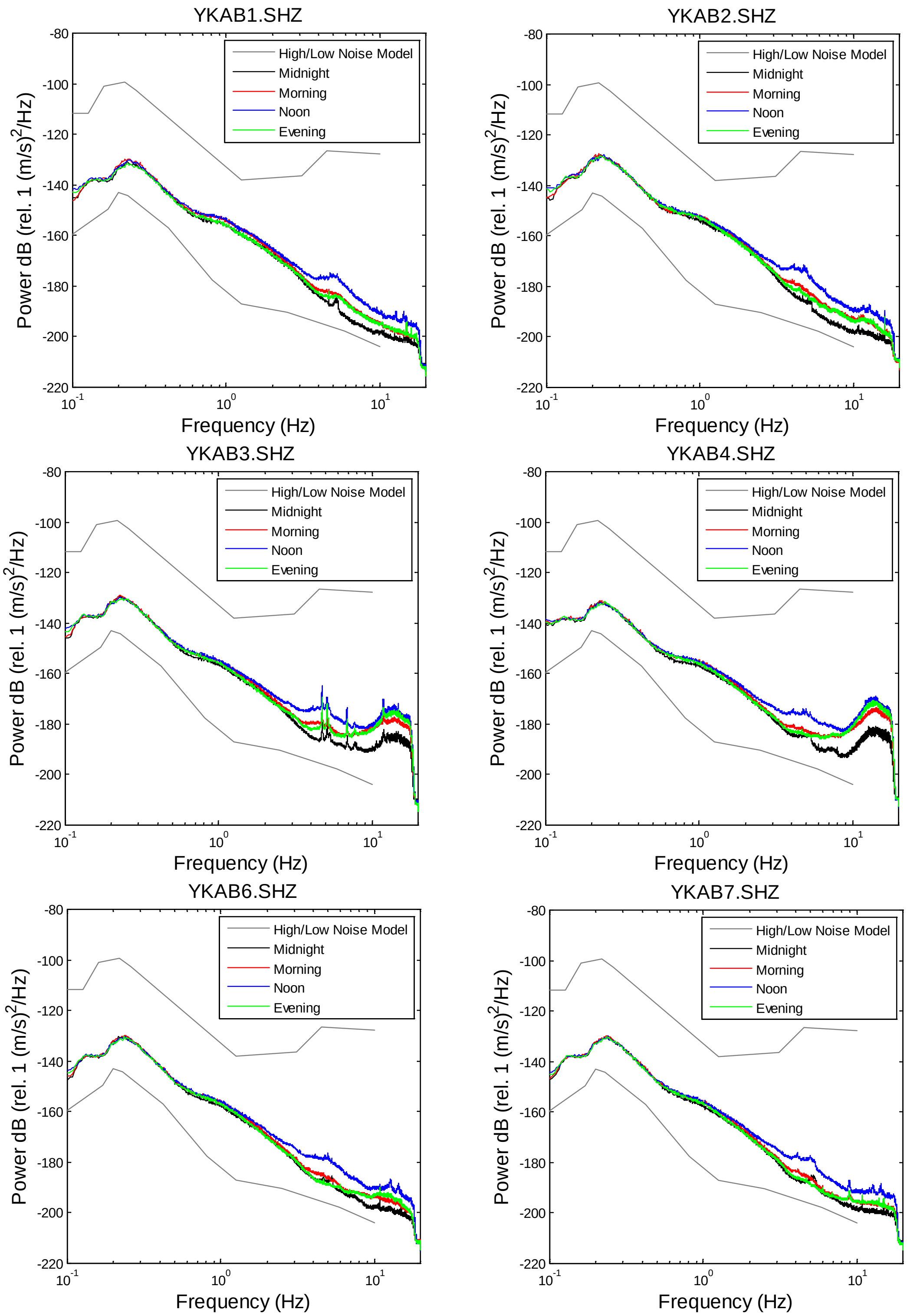


Fig. 11: Background seismic noise at YKA as a function of time of day. Local time is used at 6 hour increments of 00, 06, 12 and 18 MST (B1 – B7).

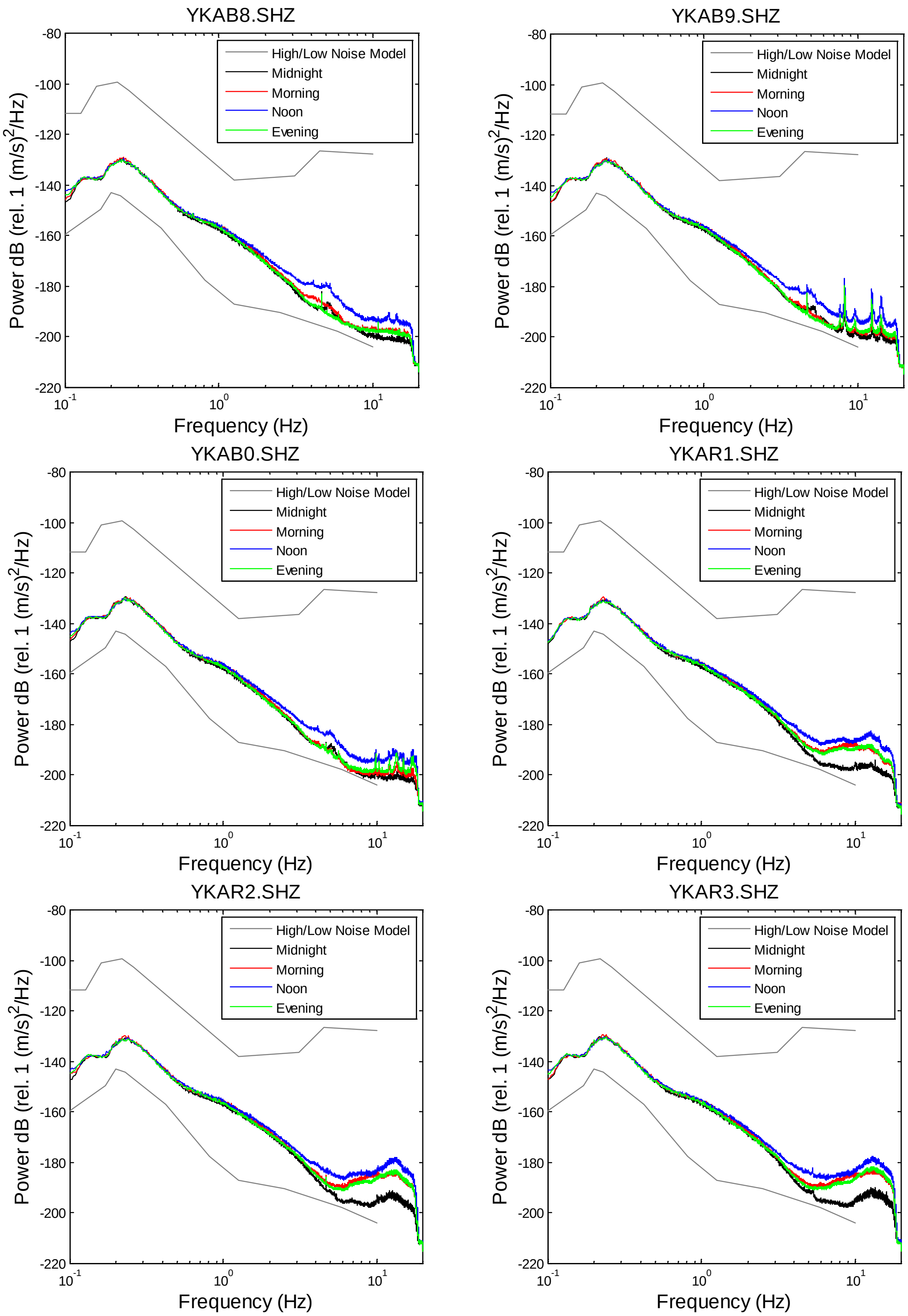


Fig. 11 (cont'd): Background seismic noise at YKA as a function of time of day. Local time is used at 6 hour increments of 00, 06, 12 and 18 MST (B8 – B0, R1 – R3).

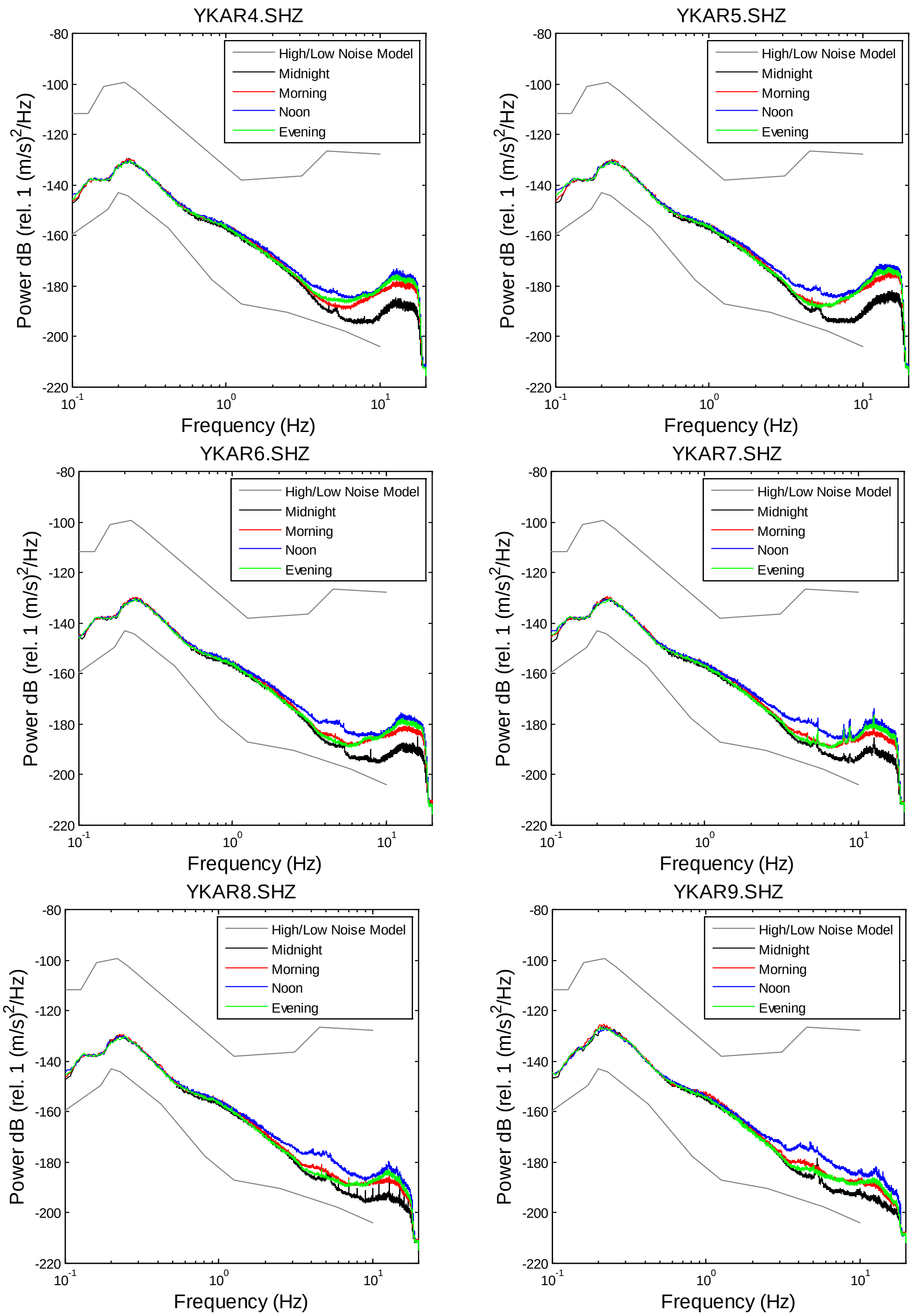


Fig. 11 (cont'd): Background seismic noise at YKA as a function of time of day. Local time is used at 6 hour increments of 00, 06, 12 and 18 MST (R4 – R9).

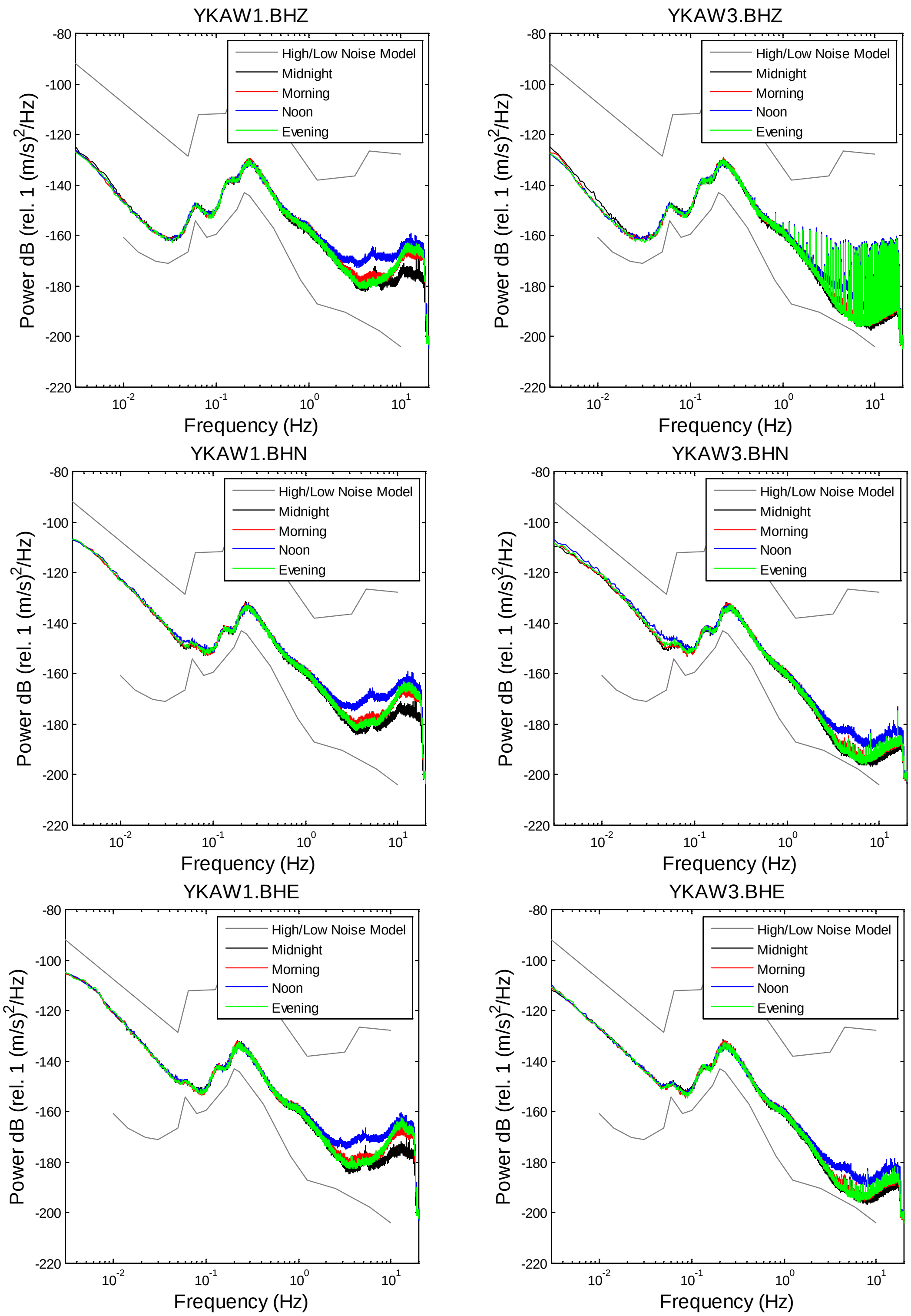


Fig. 11 (cont'd): Background seismic noise at YKA as a function of time of day. Local time is used at 6 hour increments of 00, 06, 12 and 18 MST (W1 & W3, BHZ/N/E).

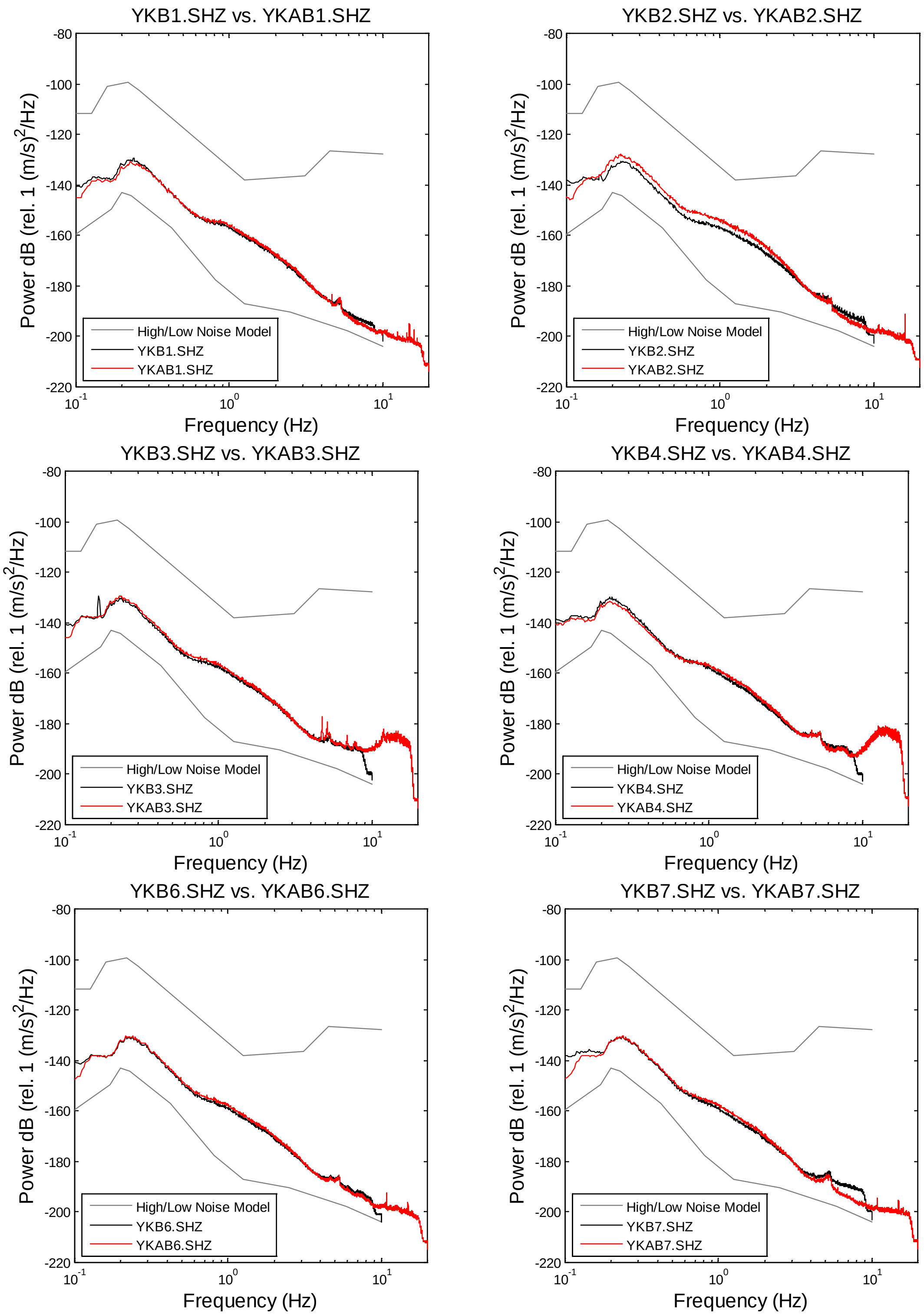


Fig. 12: Comparison of recorded seismic background noise from old (YK) and new (YKA) stations of the Yellowknife seismic array. Spectra are 90 day medians taken at local midnight, representing typical low noise conditions (B1 – B7).

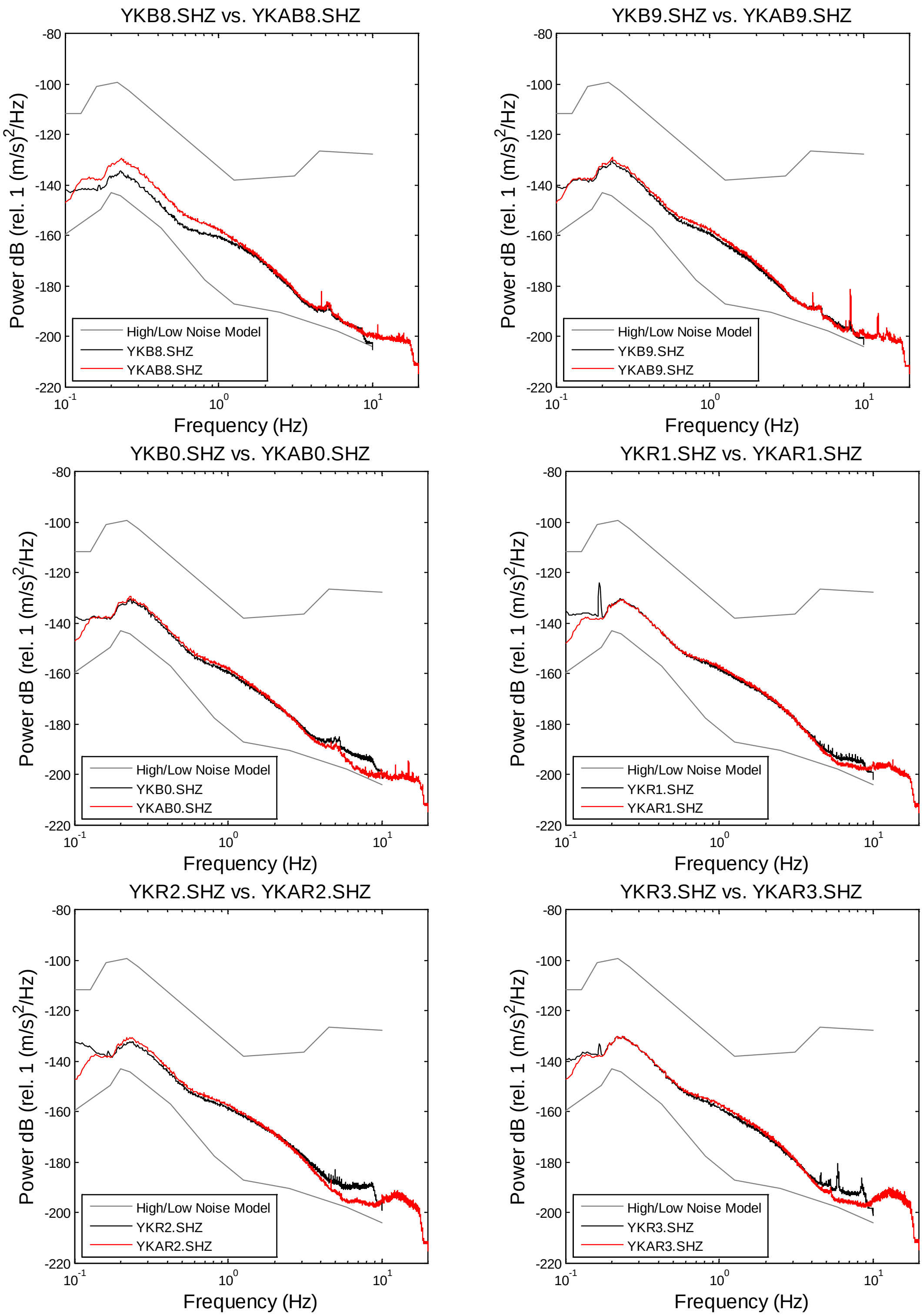


Fig. 12 (cont'd): Comparison of recorded seismic background noise from old (YK) and new (YKA) stations of the Yellowknife seismic array. Spectra are 90 day medians taken at local midnight, representing typical low noise conditions (B8 – B0, R1 – R3).

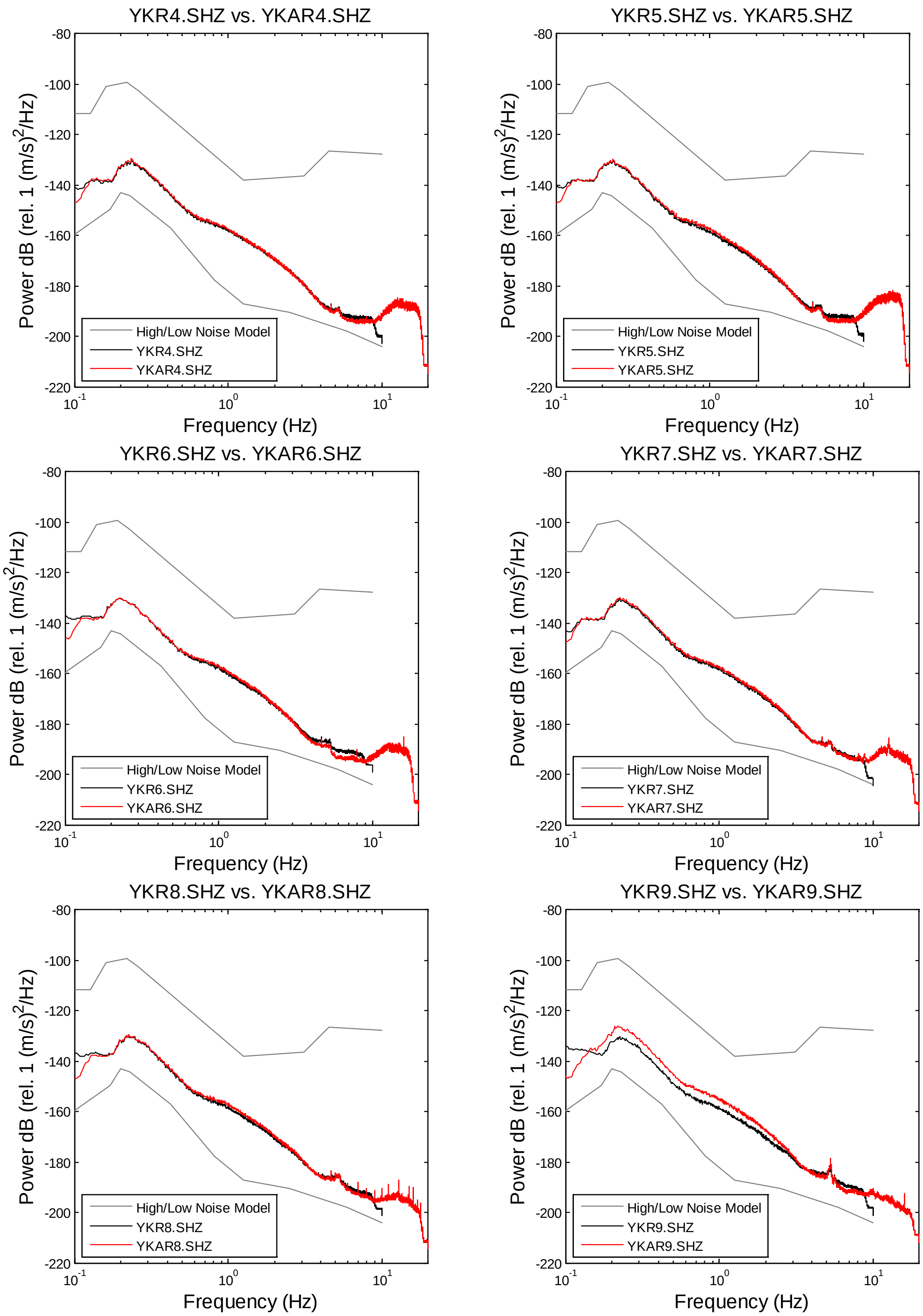


Fig. 12 (cont'd): Comparison of recorded seismic background noise from old (YK) and new (YKA) stations of the Yellowknife seismic array. Spectra are 90 day medians taken at local midnight, representing typical low noise conditions (R4 – R9).

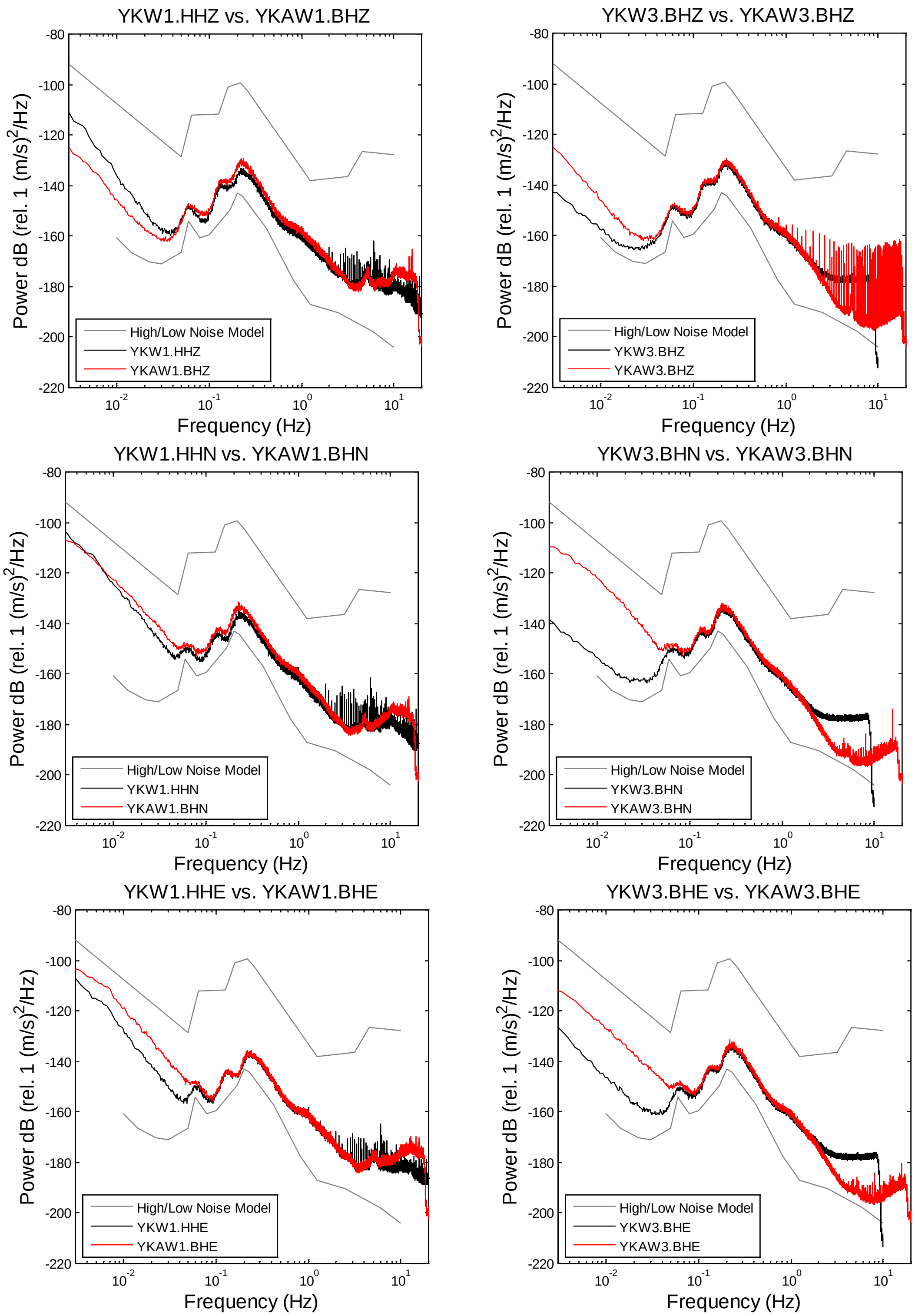


Fig. 12 (cont'd): Comparison of recorded seismic background noise from old (YK) and new (YKA) stations of the Yellowknife seismic array. Spectra are 90 day medians taken at local midnight, representing typical low noise conditions (W1 & W3, (H/B)H(Z/N/E)).

Yet the new array is not without its own issues. Excessive electronic noise and its harmonics seem to be an issue on YKAW3 at frequencies greater than ~1 Hz, primarily on channel BHZ. The cause of this is yet to be isolated, but seems likely to be related to properties of the sensor/power cable. A similar, yet less severe case also appears on YKAR8. Local noise sources appear to generate spikes at YKAB3 & YKAB9. Generally excessive noise is also seen at both broadband stations at periods longer than ~30 seconds, particularly on the horizontal channels, BHN and BHE. This is likely due to the sensor reacting to thermal and atmospheric pressure variations at periods shorter in length than the natural period of the sensor (360s). The current STS-1 broad band channels are not as greatly affected by these sources of long period noise, as they are under a state of vacuum inside bell jars, whereas the new CMG-3T sensors currently remain exposed to the air atop the vault pier.

These minor issues should be able to be readily addressable prior to re-certification of YKA.

Dynamic Range

The sensitivity settings of the new YKA instrumentation have been set in such a manner as to match, as closely as possible, the sensitivity of its predecessor. These settings and variability amongst the various components of the new system together determines the lower noise floor of the entire system. The noise level of the system (without an active seismometer reporting data) dictates the extreme lower limits for any signal detection; below this level no signal remains, just system noise. Ideally, this level should lie below well below the seismic background across the frequency band of interest. To measure this level for the new YKA short period stations, the S-13 seismometer masses at R8 & R9 were locked while still attached to the system for a period of 10 minutes. The data collected during this period represents the typical noise inherent to the system and is compared to the typical seismic background noise (Fig 13).

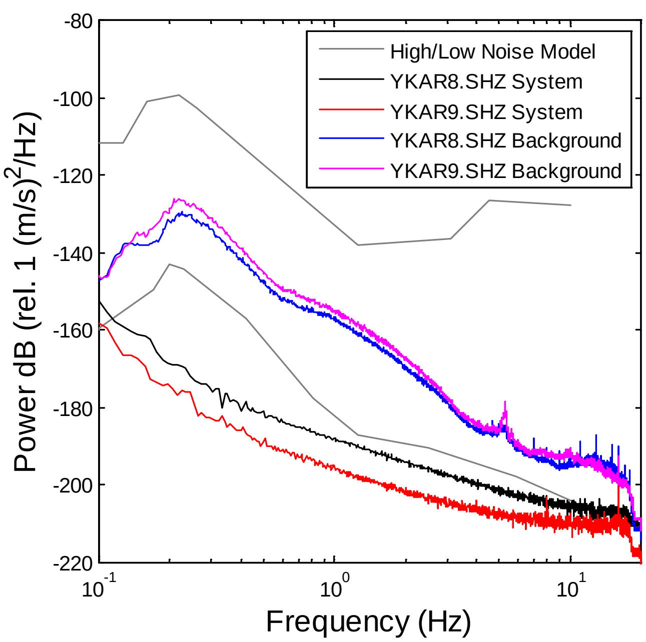


Fig. 13: System noise measurements at short period stations YKAR8 and R9 (red/black lines). Measured system noise sits below the Low Noise Model (Peterson, 1993), and indicates the limit to which a seismic event is discernible by YKA. Typical median low seismic background noise levels are shown for reference (blue/purple lines).

The results show that typical system noise lies below the Low Noise Model (LNM, Peterson, 1993) over most of the band of interest between 0.1 – 10 Hz, rising only slightly above this level at frequencies greater than 10 Hz. Viewed in the time domain, this level of noise represents approximately the first 5-6 bits worth of data of the available 24 bits, while the typical seismic background lies at the 7-9 bit level. The remaining 15 bits are then available to describe larger ground motion before software clipping of signals occurs by the digitizer (Fig. 14).

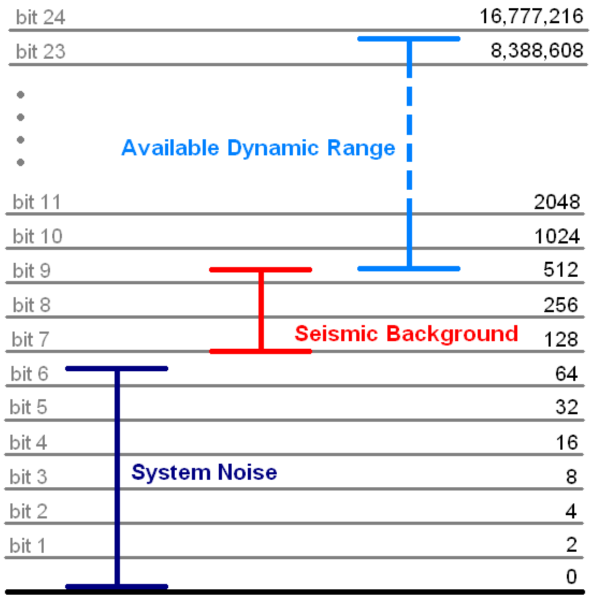


Fig. 14: Schematic diagram of the short period array use of available 24 bit dynamic range of the CMG-DM24S3EAM.

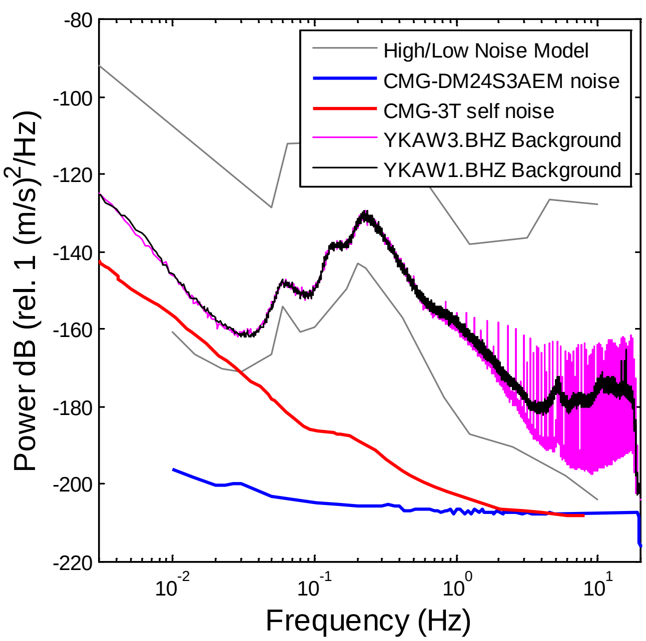


Fig. 15: Theoretical system noise for the new broadband stations at YKA. Both the measured CMG-DM24S3EAM digitizer noise using terminated input equivalent sensor impedance (blue line) and Guralp CMG-3T sensor self-noise as measured by Ringler and Hutt (2010) (red line) lie mostly below the low seismic noise model and typical low background levels for YKAW1 and YKAW3 (black/purple lines).

With a full 24 bits of dynamic range, the largest positive or negative integer value describable by the CMG-DM24 digitizer would be 2^{24} or 16,777,216. With the current average system sensitivity of 10.7068 Counts/(nm/s) (Table 1), this would correspond to a ground motion of 1.567 x 10^7 nm/s or 1.567 mm/s, or in displacement at 1 Hz this is 0.249 mm. At teleseismic distances between 20 – 90 degrees (10 km depth), this motion would correspond to bodywave magnitudes of 9.5 – 10.4 mB_BB. For regional earthquakes located in the Yukon Rockies (distance 800 km) this maximum would correspond to an earthquake magnitude of 9.0 ML, in the Beaufort Sea (1270 km) of 10.1 ML, or if located offshore Haida Gwaii region of Canada (1500 km) of 10.6 ML.

For the broadband stations at W1 and W3, a similar situation is presented with digitizer self-noise noise located at comparable levels as seen in the short period system (Fig. 15). Unfortunately, due to the nature of the active force-feedback CMG-3T sensor (as compared to the passive mechanical S-13) a direct measure of the instrument self-noise could not be made. As substitute, measurements of the sensors self-noise as measured by Ringler and Hutt (2010) is provided (Fig. 15). Coupling these two self-noises we see that both generally lie below the low noise model and approximately 10 dB below the measured median low noise levels at W1 and W3. At the other extreme, due to the lower sensitivity of the broadband instruments (Table 1), these stations will saturate differently than the short period sites. At the maximum 24 bit value, and an average sensitivity of 4.144 Counts/(nm/s), this translates to a ground motion of 4.049 x 10^6 nm/s or 0.4049 mm/s (at 1 Hz this is 64.4 μm, at 0.05 Hz (12.9 mm displacement), for a teleseismic bodywave magnitude between of 8.9 – 9.8 mb_BB or surface wave magnitude at teleseismic distances of 8.2 – 9.3 Ms_BB.

Yet, the true limit of available bit depth the CMG-DM24 is not in the digitizer, rather it lies in the front end handling of voltage. Although the 24 bit digitizing unit is able to measure signals up to a maximum voltage of 48 Vp-p, the front end only accepts input to 40 Vp-p. Thus the true bit depth closer to 23.74 bits, however, this does not significantly change the upper limit thresholds described above.

As the likelihood of such catastrophic earthquakes is quite low, and the desire of the array is primarily to monitor for rather small signals near, at or below the seismic background noise, the overall sensitivity of the array could be safely increased to provide higher fidelity of the seismic background.

GPS Timing

A new feature introduced to the Yellowknife seismic array and previously unavailable to its predecessors is precise absolute time provided by individual GPS clocks at each array element. Prior to the 2010-2013 upgrade the absolute time provided for each station of YKA was provided by a central GOES (and later a modified GPS) clock located at the Central Facilities Building and telemetered to each station via radio (GSC, 1989). A time correction was then added to account for the telemeter & propagation time delay from the CFB to the out stations. Unfortunately the value of this time correction has not been documented.

To determine the accuracy of the original YKA central clock and timing of data from the previous array, several impulsive teleseismic signals observed by both arrays, were used. Several impulsive and high signal to noise teleseismic signals recorded between July through September 2013, were cross-correlated between new and old station data streams using the following technique.

Once a signal to be used was identified, a five minute data segment around the signal was extracted from both new and old containing the signal. Both traces are then interpolated to 1000 Hz sampling and cross-correlated. The peak lag of the cross-correlation is then referenced to the zero lag peak of the autocorrelation of the new YKA data trace. The lag difference between auto and cross-correlations is then the time offset between the new YKA GPS clock and the old YKA central radio telemetered clock (Table 3). A side benefit of the cross correlation procedure is that the amplitude of the cross correlation normalized by the peak of the autocorrelation gives an overall assessment of the amplitude ratio of the old YKA data and the new. These results will be discussed in the next section.

Station Name (STN.CHAN)	Mean offset from new GPS clock (seconds)	Cross-correlation Coefficient (Old / New)	Cross-correlation Coefficient (New / Old)
YKB1.SHZ	-0.090 ± 0.013	0.805 ± 0.034	1.244 ± 0.054
YKB2.SHZ	-0.088 ± 0.006	0.808 ± 0.031	1.239 ± 0.049
YKB3.SHZ	-0.098 ± 0.013	0.748 ± 0.025	1.337 ± 0.046
YKB4.SHZ	-0.078 ± 0.016	0.796 ± 0.033	1.258 ± 0.050
YKB6.SHZ	-0.097 ± 0.011	0.779 ± 0.025	1.285 ± 0.042
YKB7.SHZ	-0.091 ± 0.008	0.777 ± 0.027	1.289 ± 0.047
YKB8.SHZ	-0.125 ± 0.014	0.569 ± 0.045	1.767 ± 0.143
YKB9.SHZ	-0.099 ± 0.010	0.734 ± 0.037	1.366 ± 0.073
YKB0.SHZ	-0.102 ± 0.011	0.735 ± 0.037	1.364 ± 0.072
YKR1.SHZ	-0.094 ± 0.021	0.772 ± 0.027	1.297 ± 0.046
YKR2.SHZ	-0.102 ± 0.028	0.738 ± 0.086	1.374 ± 0.192
YKR3.SHZ	-0.091 ± 0.015	0.776 ± 0.038	1.291 ± 0.068
YKR4.SHZ	-0.097 ± 0.023	0.753 ± 0.031	1.329 ± 0.054
YKR5.SHZ	-0.096 ± 0.015	0.764 ± 0.026	1.310 ± 0.044
YKR6.SHZ	-0.095 ± 0.011	0.784 ± 0.030	1.277 ± 0.050
YKR7.SHZ	-0.885 ± 0.517 *	0.759 ± 0.028	1.319 ± 0.050
YKR8.SHZ	-0.096 ± 0.007	0.749 ± 0.024	1.336 ± 0.043
YKR9.SHZ	-0.093 ± 0.010	0.764 ± 0.027	1.315 ± 0.045
YKW1.HHZ	-0.008 ± 0.003	0.966 ± 0.016	1.035 ± 0.016
YKW1.HHN	-0.011 ± 0.006	0.985 ± 0.020	1.016 ± 0.021
YKW1.HHE	-0.010 ± 0.004	1.007 ± 0.080	0.998 ± 0.072
YKW3.BHZ	-0.132 ± 0.057	0.899 ± 0.006	1.113 ± 0.008
YKW3.BHN	-0.029 ± 0.004	0.901 ± 0.041	1.112 ± 0.047
YKW3.BHE	-0.239 ± 0.075	0.915 ± 0.019	1.093 ± 0.023

* Station RD3 clock confirmed to be drifting at approx. 0.5s/month at time of measurement

Table 3: Timing and amplitude ratio results of cross-correlation between old and new YKA data using impulsive teleseismic signals over a three month period.

In general we see that the old Yellowknife array data is time stamped approximately 0.10 seconds earlier than the GPS time stamps of the new clocks. This value is consistent across nearly all 18 new GPS clocks for the short period sites, with the exception of YKR7 where it was determined that the RD3 internal clock was drifting (later confirmed with technicians) at a rate of ~0.5 sec/month. The reason for a slightly fast central clock at the short period sensors is unknown, however, as no modifications to the clock have been made since prior to its IMS certification in 2000, the fast clock may be a fixture of the short period array since at least that time. As typical global location residuals using YKA may tend to larger in size than this value, it may not be unsurprising that a slightly fast clock would go unnoticed.

Finally, timing at the only remaining operational broadband STS-1 station at W3 was also tested in a similar way. It was found that despite the three Streckeisen instruments being connected to the same YKD digitizer, all three channels were found to lag ahead of the new onsite GPS clock by differing amounts. Of the three channels, BHN, the north-south component was the only component to be effectively “on-time” with a mean correlation lag of -0.029 seconds or less than a sample (0.05s or 20

Hz). The remaining channels, BHZ (vertical) and BHE (east-west) were found to lead the GPS clock by 0.13 and 0.24 seconds respectively. As this broadband station is designed for primarily recording long period surface waves, it is reasonable to assume that such small timing errors could go unnoticed during regular processing. Timing at broadband station W1 was also performed in coordination with the GSC operated, non-IMS broadband sensor (YKW1.HHZ/N/E) and confirmed that the timing of all channels were on-time with the new IMS sensor and clock. Note that channels YKW1.HHZ/N/E are digitized with a GD2 (Geophysical Digitizer Model 2) which also has its own independent GPS clock.

Amplitude, Period & Magnitude

As the new Yellowknife system is designed to be used in a continuous monitoring system and a worthy successor to its predecessors, the ability of the new array to reproduce the observations of the previous array and the ability to compare current & future observations of the new YKA with its previous incarnations is paramount. To assess the performance of the new array with that of the old YKA, amplitude results of the cross-correlation procedure were investigated, array responses examined, and three months of teleseismic observations were evaluated as measured on both systems, then compared.

As discussed in the previous section on the details of the 2013 Upgrade, the locations of the instrument vaults has moved slightly from its predecessor due to the degradation of the old vaults. Moving of the vaults introduces slight changes to the overall response of the array. To evaluate these changes the YKA array response is computed for frequencies of 0.5, 1.0 and 3.0 Hz, spanning the frequency band of interest for teleseismic signals (Fig 16). The changes observed between new and old array are slight, varying between ~1% at 0.5 Hz and ~12% at 3.0 Hz or ±0.04 and ±0.6 dB, respectively. These changes are confined primarily to the outer side lobes of the response, with larger differences occurring at higher frequencies, to be anticipated as the vault locations were moved less than 10m at each site, while the array aperture spans 25 km. The primary lobe remains virtually unchanged.

Between 20 and 90 degrees range from YKA, some 365 events occurred between July and September 2013, ranging in magnitude between 4.0 – 7.0 mb and these events form the basis of the comparative dataset. For each event, 5 minute data segments were taken to encompass the initial P arrival set as predicted by ak135 travel times (Kennett et al., 1995) for both arrays. For both arrays, each short period channel was response corrected, after which channels were beamformed along the predicted event back-azimuth and slowness. The resulting beam traces were then filtered with a World-Wide Standardized Seismographic Network (WWSSN) short period sensor response and for each array beam, the peak displacement amplitude of the P arrival phase measured along with its period using the nearest zero crossings (ISC, 2011). From these measurements a body wave magnitude (mb) was computed.

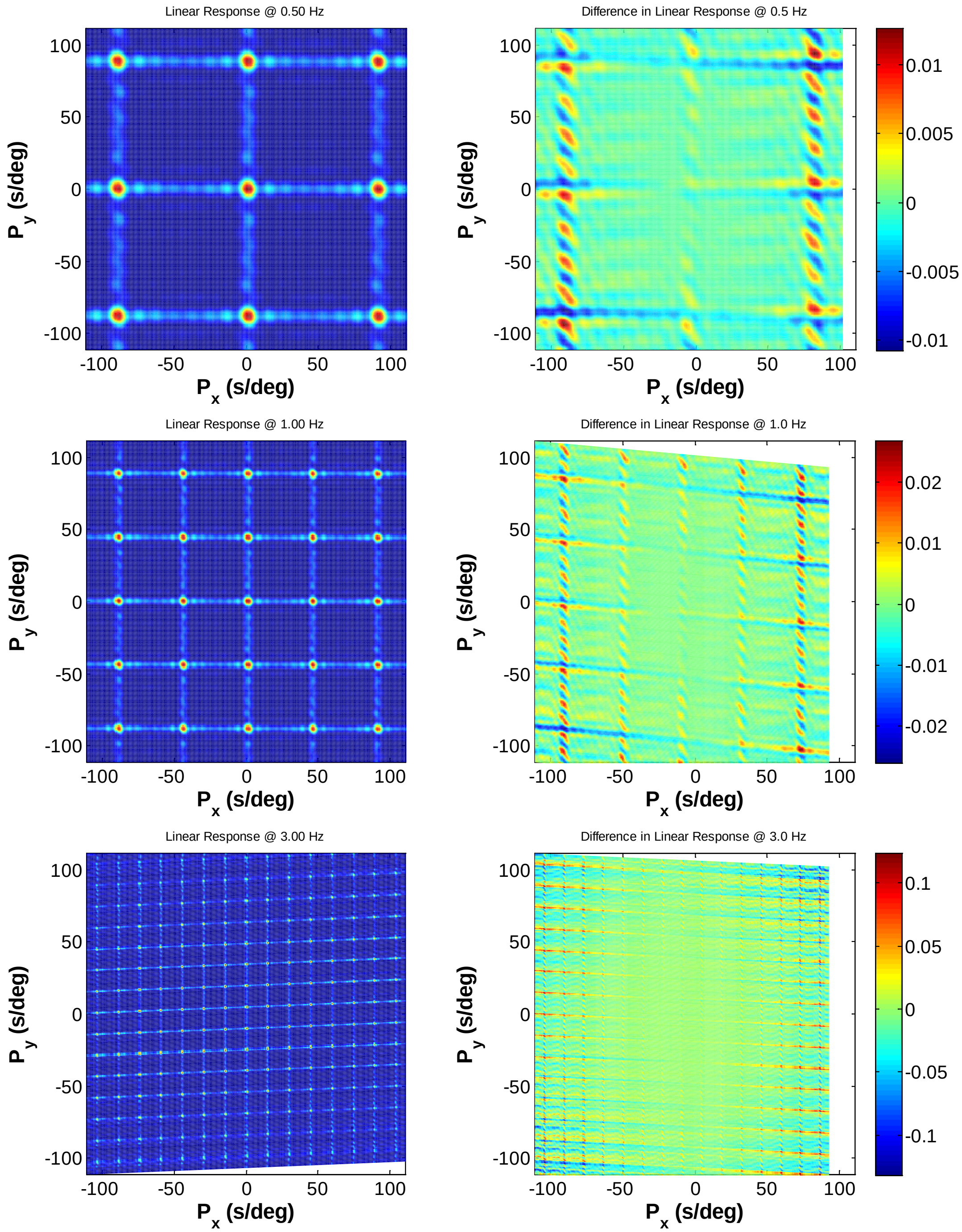


Fig. 16: Array responses for the new YKA at three frequencies (left) and the differences relative to its predecessor (right). Measurements are shown with a linear scale normalized to 1.0 at the response peak at (Px, Py) of (0, 0). (Top) 0.5 Hz, (middle) 1.0 Hz, (bottom) 3.0 Hz. Residual magnitude scales are also linear, thus a 10% change in value would be represented as 0.1.

Comparing the measured amplitudes of the 365 events it is seen that in general the amplitudes agree quite well across the nearly 3 orders of magnitude measured (Fig 17), however, the new array systematically has slightly higher amplitude values by about 17-20%. This is consistent with observations made using cross-correlation, where the short period channels are larger by ~33% (Table 3). In terms of measured periods, these appear to again agree well. As the WWSSN short period displacement response is a narrow analog sensor response centered on 0.75 - 1 second periods, the measured periods tend to cluster about the 0.75 – 1.5 Hz region (Fig 18). Approximately 10% of the measured periods deviate from the 1:1 line with periods higher than 1.5 seconds as one array or the other measures a somewhat higher period due to ‘kinks’ near the zero crossing where the automated picking routine used becomes confused. Overall, this does not significantly affect the magnitude results (Fig 19). Here the higher on average amplitudes measured on the new YKA can been seen to result in systematically higher magnitude estimates over the old YKA by 0.103 magnitude units.

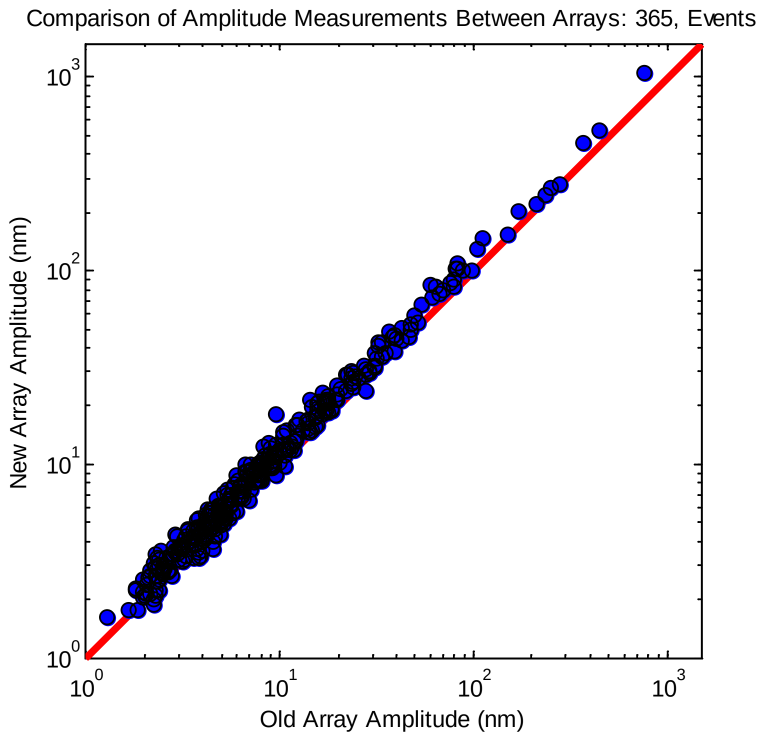


Fig. 17: Comparison of amplitudes from 365 teleseismic signals from global 4.0 – 7.0 events between July – September 2013, as observed by the new and old Yellowknife seismic arrays. Red line indicates a 1:1 correspondence.

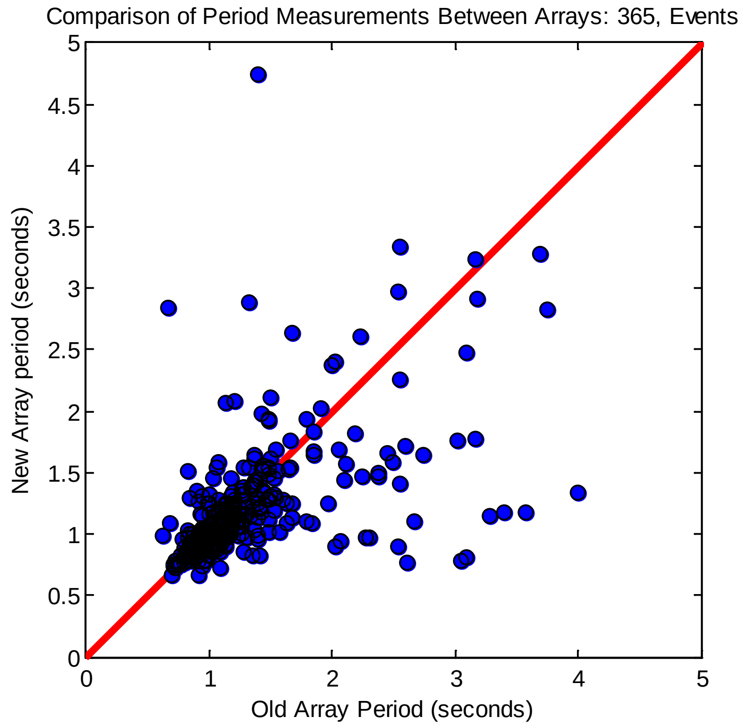


Fig. 18: Comparison of dominant periods from 365 teleseismic signals from global 4.0 – 7.0 events between July – September 2013, as observed by the new and old Yellowknife seismic arrays. Red line indicates a 1:1 correspondence.

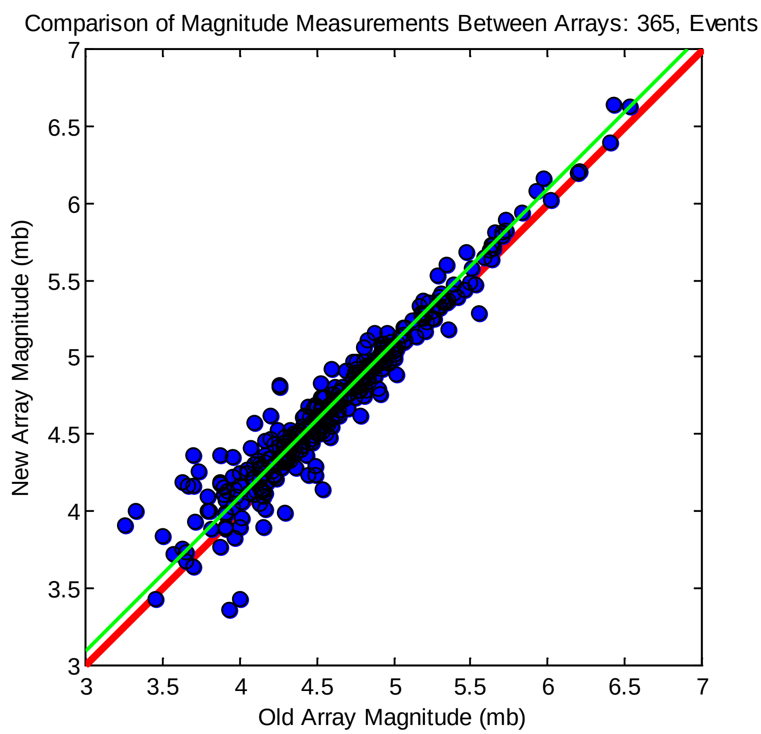


Fig. 19: Comparison of magnitude measurements from 365 teleseismic signals from global 4.0 – 7.0 events between July – September 2013, as observed by the new and old Yellowknife seismic arrays. Red line indicates a 1:1 correspondence. Green line is a fit to observed correspondence, resulting in an offset from the 1:1 by +0.103 magnitude units.

The higher estimates in magnitude initially seem worrying as the intent was to match the new array observations to that of its predecessor. Yet as seen from an independent study, performed by the Science Applications International Corporation (SAIC) in 2010 validating instrument responses of the IMS network, they demonstrated that the old YKA array was systematically low in its magnitude observations (Stevens et al., 2010). In fact, the old array was systematically low in mb estimates by -0.07 ± 0.021 magnitude units as compared to global averages in the IMS (Fig. 20). This translates to an amplitude deficiency at YKA of between ~11 – 19%, approximately the same as the new amplitudes are in excess of the old (Fig 17). Thus overall, the new array appears at the moment that it should be in better agreement with IMS global network magnitude estimates.

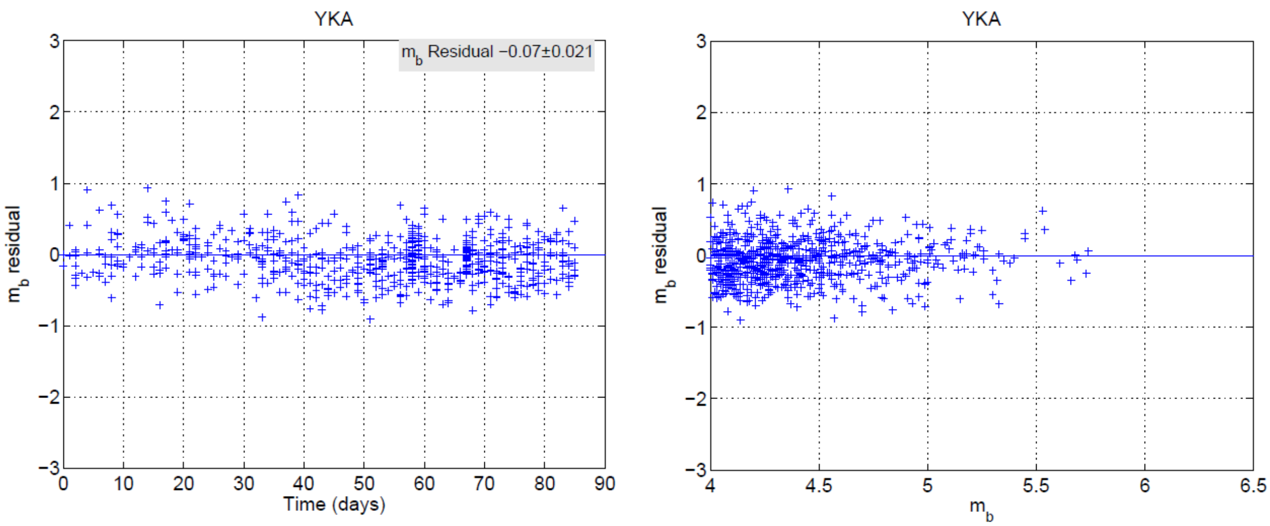


Fig. 20: Global bodywave magnitude residuals for YKA as compared to the IMS network computed from ~90 days of teleseismic observations from November 2009 to January 2010. A residual offset of -0.07 ± 0.021 magnitude units is seen. Reproduced from Stevens et al. (2010).

Recommendations

Overall the performance of the new Yellowknife seismic array is very satisfactory. Despite the near complete replacement of the entire infrastructure, both in hardware and software, the new YKA performs as well or better than its predecessor in many aspects. Holding this view in mind, there are still minor issues which should be resolved prior to the array's re-certification if possible. These are as follows in no particular order.

1. The electronic noise visible on the broadband station YKAW3, particularly on vertical channel, BHZ. This noise at its maximum is up to 30dB above the seismic background noise at all frequencies greater than ~1 Hz, and visible on the horizontal channels at lower levels, making the higher frequencies of this data nearly useless. The noise is not of seismic origin and may be due to electronic noise induced in the cable connecting the sensor to the digitizer.

2. Identification and removal of similar but minor electrical noise at YKAR8.

3. The thermal and atmospheric induced noise on the new broadband instruments should be addressed. If the new CMG-3T broadband instruments are to permanently replace the STS-1's at W1 and W3, then the noise below ~30 seconds needs to be significantly reduced. Currently noise levels at these frequencies on the CMG-3T lie 5 – 10 dB higher on the vertical channel

and 20 – 30 dB higher on the horizontal channels than their equivalents on the STS-1. The reason for this difference is likely due to the exposure of the new digitizer to the elements within the broadband vaults atop the pier. Some degree of thermal insulation and decoupling to the atmosphere should be applied to the sensors to minimize CMG-3T instruments response to pressure and thermal variations at long periods. The STS-1s excel at this as they are placed under a partial vacuum.

4. Identification of the source and its reduction of the HF noise at YKAB9.

5. Adjustment to the short period array gain settings. Currently there is very little separation between the level of the system noise (5-6 bits) and the background seismic noise (7-9 bits). As the primary goal of the short period array is to “dig” into the background noise to identify very small events, the current setup and settings limit this ability. It may be desirable to have at least one or two bits of separation between system & background noise. The most readily applicable method available method to achieve this is to adjust the level of the current system noise. There are several means by which this may be achieved with varying degrees of difficulty which will not change the current system sensitivity.

    a. Move the S-13 preamplifiers from their current position within the battery vault to the seismometer vault. The current setup requires that the preamplifier be inside the battery vault for ease of technician maintenance. The downfall of this positioning is that the seismometer cable to the pre-amp is 40m long. Along this length, the weak seismometer signal is analog and is subject to induced noise. Upon reaching the pre-amp this noise is then amplified along with the seismometer signal by a factor of 40 before digitization. By moving the pre-amp to the seismometer vault, the seismometer cable is short and less subject to noise prior to amplification. Afterwards the analog signal is still subject to noise along the 40m cable, however, that noise will be 40x smaller in relation to the seismometer signal before digitization. The downside of this method is that power must now be supplied to the seismometer vault using one of the spare wires in the current conduit.
    b. Move the pre-amp and the digitizer to the seismometer vault. Similar to the previous method in that induced noise in the analog signal is reduced, however, now the 40m long cable carries a purely digital signal to the communications equipment housed in the battery vault. The downside to this solution is that not only must power be supplied to the vault, but the 40m cable itself must be modified/replaced from a sensor cable to a digitizer cable. As well, the digitizer requires a GPS signal and a 40m GPS cable stretches the limits of what is reasonable for this device. Thus the GPS antenna would need to be moved from its current position atop the solar/radio tower to the vault.
    c. Do nothing. If the current settings, system noise levels and seismic background levels are within acceptable tolerances within the bandpass of interest, or it is shown that little difference is made by moving the pre-amp or digitizer to the system noise, then no modifications need be performed.

In order to determine which of these options is the correct method to pursue, it is suggested that a full scale test be carried out either at the Geomagnetic Laboratory short period test site in Ottawa or at the central facilities building in Yellowknife using spare equipment.

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