RADIAL ELECTRONICS

# Embedded Magnetics Reliability Report

This report presents the initial reliability results for a 10 Gigabit Ethernet media filter that was constructed with embedded magnetics technology. The devices were fabricated with standard printed circuit board (PCB) materials and processes. The data collected herein represents a typical production lot. Samples underwent stress testing consistent with the requirements of modern telecom and datacom systems. The products demonstrated the consistency and performance of a high reliability printed circuit board. The report summarizes reliability testing and results for Radial's embedded magnetics process[1].

## Background

Embedded magnetic technology utilizes printed circuit board materials and processes to fabricate transformer and inductor devices. The devices in this report were fabricated by inserting small ferrite cores into an FR-4 substrate and encapsulating them with low stress epoxy. Printed circuit layers were laminated to the top and bottom surface the inductive "windings" were imaged and etched using standard PCB processes. to produce the device windings. Conductors on the top and bottom surface were then interconnected using plated-through-hole (PHT) vias, to provide continuous windings around the ferrite cores. Other than the insertion and encapsulation of the ferrite cores, the construction essentially used the same processes and materials as a standard PCB. The 10G Ethernet media filter has 8 transformer elements and is a 4 layer design. Four transformers are implemented within the bottom 2 layers and another 4 transformers are implemented on the top two layers. Figure 1 shows the media filter and Figure 2 depicts the PCB stack-up

---

[1] The devices were fabricated by Somacis Graphics, Shenzen, under the sponsorship of Bel Components.

Jim Quilici
October 2011

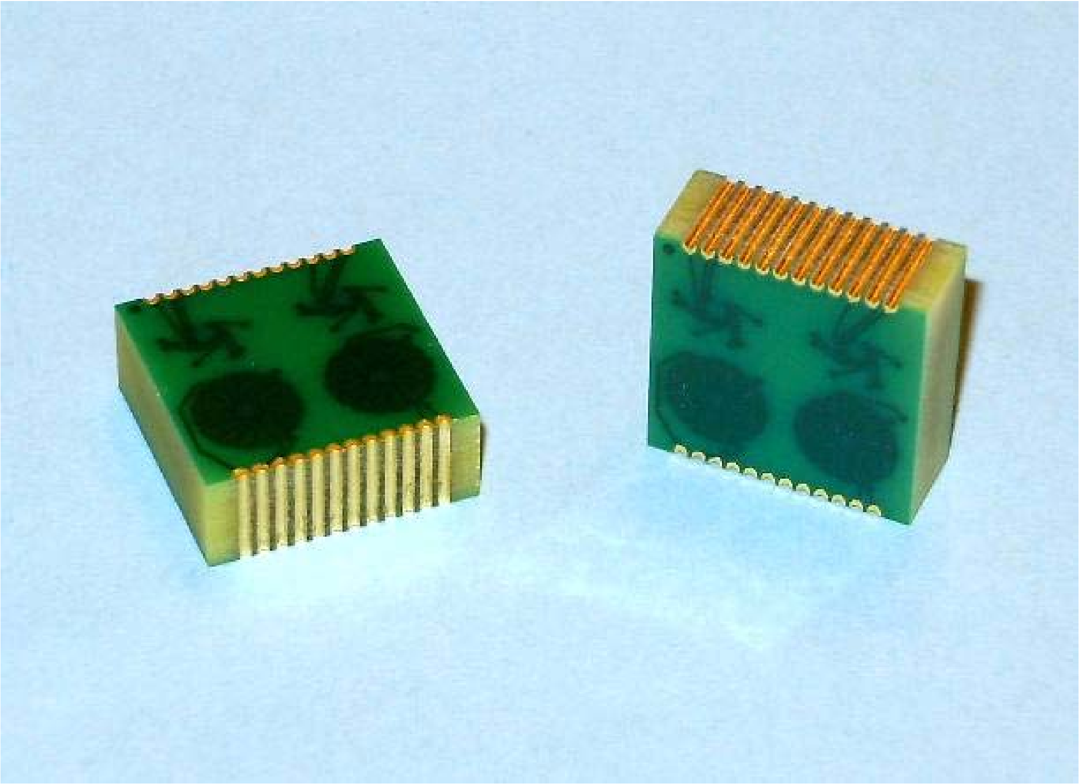

Figure 1. Embedded Magnetic Media Filters

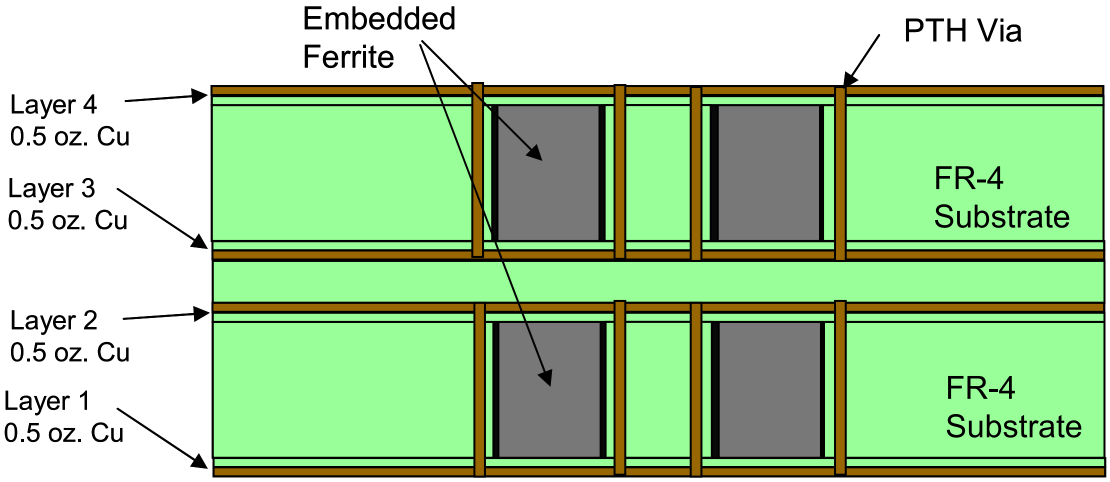

Figure 2. PCB stack-up

## Test Descriptions

The reliability testing builds off 50+ years of PCB manufacturing. The devices are constructed with the same materials and processes that have been qualified on countless occasions in the past. What sets these devices apart from a standard PCB is the insertion and encapsulation of ferrite[2] cores into the FR-4 substrate. Industry standard tests were used to evaluate the parts.

- Thermal Cycle
- Highly Accelerated Stress Test (HAST)
- High Pressure & Temperature Stress Test
- Low Temperature Storage
- High Temperature Storage
- Solder Reflow
- Hipot

This report documents the initial reliability analysis of the embedded magnetic process. It is the foundation for future product development. Once a device is in production, 3 consecutive manufacturing lots should be tested during pre and early production. After full production release, periodic screening should be implemented to monitor the process. Failure statistics should be compiled and reliability failures should undergo in-depth failure analyses to track failure mechanisms and identify process and design modifications.

## Description of Tests

As with most microelectronics, a disciplined design methodology is essential to produce a reliable part. Material selection and circuit layout are both critical to the device's performance under environmental stress. The embedded ferrites are sensitive to compression and tension forces. A low shrink epoxy is selected and special attention is given to the curing parameters. Other considerations are the pressures and temperature settings used during the FR-4 lamination process. Even with careful selection of materials, there is often residual stress on the ferrite cores after processing. Mismatch in the material thermal expansion coefficients contributes additional stress as the part heats and cools during operation. Thermal cycling, HAST, Pressure Cooking

---

[2] **Ferrites** are chemical compounds that combine ceramic materials with iron oxide ($Fe_2O_3$). In terms of hardnerss and thermal expansion, the materials have exhibit material properties similar to a ceramic.

and IR Reflow are key to determining if the parts will fail in the field under normal thermal stress. Low and High temp storage also evaluate the thermal match, yet are generally less stressful than the other thermal tests yet are industry standards. For the Ethernet application, voltage isolation is another important requirement. Selecting materials with specific dielectric properties and withstanding voltages are important for meeting Hipot and achieving electrical performance at high frequencies.

Prior to stress testing, the devices are visually inspected for defects and tested for opens, shorts and Open Circuit Inductance (OCL). After environmental stress, the devices are re-tested for opens, shorts and changes in Open Circuit Inductance (OCL). After stress testing, they were once again inspected for any visual defects, such as delamination, discoloring and material leaching. Often the embedded magnetic devices will have other electrical requirements, over an RF frequency band. In most cased the high frequency performance is defined by the circuit artwork and the material dielectric properties. Generally, the RF performance does not shift during stress testing and it is sufficient to simply test opens, shorts and OCL. Table 1 summarized the reliability tests performed on devices from the initial R&D build.

**Table 1 Embedded Magnetics Development Reliability Tests**

| Test Name | Method | Conditions | Duration / Frequency | Sample Size |
|---|---|---|---|---|
| Thermal Cycling | Mil-Std-883, method 1010 | -40°C to 100°C, 20 min dwell time | 100 cycles | 10 |
| Highly Accelerated Stress Test (HAST) | JEDEC Spec 22-A110 | 85°C, 85% relative humidity (RH), | 50 Hrs. 100 Hrs. 200 Hrs. | 10 |
| Autoclave, Pressure Cook + Humidity | JEDEC JESD22-A102 | 121°C, 15PSI for 96 hours then 85°C, 85% RH | 500 hours | 10 |
| Low Temperature Storage | Mil-Std-810 method 502.4 | Storage -55°C unbiased | 100 Hrs. | 10 |
| High temperature Storage | Mil-Std-810 method 501.4 | Storage 150°C unbiased | 100 Hrs. | 10 |
| Solder Reflow | JEDEC-J-STD-20 | Max. Temp. 255°C -265°C, 20 second dwell time | 3 passes | 9 |
| Hipot | | 1500 Vrms | 60 sec. | 6 |

Notes

1. The devices are passive and were not biased in each test except Hipot.
2. Each device has 4 channels

During reliability testing, there are 5 primary failure mechanisms that can occur

1. Opens Circuit: possible failure could be cracking of via barrels, due to thermal expansion or delamination.
2. Short Circuits: Most short circuit failures will come in-process, during the plating step, and will be screened out before final test. During stress testing, a short circuit could possibly occur due to moisture penetration into the package or dendrite growth and copper migration. These types of failures are rare in printed circuits and are not likely with the embedded magnetic construction and materials.
3. Low OCL: The ferrite cores are hard ceramics. They are robust, and can withstand the stresses imposed by expansion and contraction of the surrounding polyamide materials. While they will not crack, there is still an issue with maintaining an OCL value. The ferrite permittivity diminishes when compressed, resulting in a drop in the winding OCL. The 10G media filters are designed to have an OCL > 150 uH, and drops of 50uH have been observed due to epoxy stress. Often, the parts will regain some of the OCL after thermal cycling or a couple of IR reflow cycles. When the polymer materials cycle through their glass transition temperatures, the internal polymer chains in the epoxy can relax to some degree. Micro-cracks in the ferrite are a more detrimental problem. Devices with micro-cracks will exhibit a very low OCL (≈ 2-5uH). Generally, micro-cracks will occur in-process and devices will be screened-out prior to reliability testing. If they do occur during reliability testing, the likely stress tests would be thermal cycling and IR reflow. The epoxies and laminates used in the embedded magnetic design have been specifically selected to minimize stress on the ferrite cores and avoid these failures.
4. Visual “pop-corning” or delamination: Delamination may be evidence of moisture entrapment or material leaching. Most likely, the Autoclave and HAST testing will bring-out these failures in a marginal design. While delamination may not create an electrical failure, is indicates a vulnerability that may eventually lead to an open via barrel or short due to corrosion.
5. Voltage Breakdown: The embedded magnetic designs rely on the material properties of the polyimide laminate and polymer solder mask to provide high voltage isolation. Both materials provide over 500 V/mil of isolation, which is

sufficient for the application. Design rules must be followed to assure there is sufficient clearance between high voltage stress points in the circuit. If the design rules are followed, then Hipot failures could indicate the need for better process control during lamination and the application of solder mask.

**Thermal Cycling:**

This test induces stress due to the different expansion coefficients of the various materials. This test gauges the components response to temperature changes and the construction quality. If the materials are not well matched, cycling the device between temperature extremes can eventually cause an open circuit. Radial has developed two encapsulation options for embedded magnetics; one using a low shrink epoxy and the other using a silicone formulation. The silicone formulation has less stress on the ferrite cores and yield higher OCL values. In comparison, the epoxy material has as lower thermal expansion coefficient than silicone, yet applies more compression stress on the ferrites. The epoxy material is harder, which is also beneficial for drilling and machining. With the epoxy encapsulation, thermal cycling will often release stress in the polymer chains, providing a 5% to 20% increase in the OCL. In production, a thermal cycling or IR reflow step may be introduced in production, to service as both an annealing step and to also force infant mortality in marginal devices. This annealing step should be done prior to final test. Those devices that use Silicone encapsulation do not exhibit the same change in OCL after thermal cycling; however passing the devices through the IR reflow oven could still serve as a stress test prior to final test.

For the reliability test, devices were cycled 100 times. Future investigations will continue the cycling the parts in increments of 100, to determine the point of failure.

**HAST:**

Although the magnetic elements are covered in polyimide, the combination of heat and humidity will often accelerate failures within microelectronic devices. HAST can induce moisture penetration into the lamination, which could eventually lead to moisture entrapment and corrosion. In the HAST test, parts are submitted to an elevated temperature of 85°C and 85% relative humidity for extended period of time. The parts are visually inspected and tested electrically, after each 50, 100 and 200 hour periods.

**Autoclave:**

Similar to HAST, the autoclave test stresses the part under heat and temperature. The added element is 15 PSI of pressure, which is intended to force moisture into any voids or gaps in the laminate composition. If the lamination is marginal, the autoclave can cause opens due to delamination or shorts due to moisture penetration.

**High Temperature Storage:**

High temperature storage screens for failures that are accelerated by heat. This is an industry standard test and generally has more impact on active devices. If anything, the elevated temperature can relax the polymer chains in the encapsulation and increase the OCL value. If the design or process is marginal, the epoxies may out-gas any residual solvents or moisture or degrade and become causing embattle. The materials selected for these designs have high glass transition temperatures, making them stable at 150°C.

**Low Temperature Storage:**

Materials generally contract at low temperature, placing compression forces on the ferrite cores and internal circuitry. These stresses are generally released after the temperature is brought back into the operating range (0° to 70°C).

**Solder Reflow Test:**

One of the harshest environments that a component will see is during surface mount assembly. Within the IR reflow chamber; the device will first soak at 180°C for a minute before being elevated to a peak temperature of 260°C for a 10 second. Materials must also be carefully selected assure that they do not melt or deform at these temperatures. In most cases the thermal mass of the component is high enough that the device will not reach peak temperature throughout. Even still, large temperature gradients can develop across the body, which could ultimately lead to delamination or tearing open a plated via. In most cases, the oven temperature will also exceed the glass transition temperature of the polymer materials. Fortunately, the time at peak temperature is brief enough that polymer chains do not re-organize. If anything, the temperature cycle has been shown to increase the device OCL values, due to stress release in the polymer chains.

**Hipot:**

Hipot is often regarded as an electrical requirement, rather than a reliability test. It is, however, an indication the integrity of the materials and process. The embedded magnetic designs rely on the withstanding voltages of the FR-4 laminate and solder mask, to meet the Hipot requirement. For the R&D reliability test, the parts were tested at 1500 Vrms for 60 seconds. Subsequent testing stressed the devices to the point of failure, which occurred around 1920 Vrms.

## Reliability Results

The results are rather simple. Seven groups of samples completed the environmental stress and reliability tests outlined in Table 1 and all passed. OCL data for Thermal Cycling, HAST and IR Reflow is summarized in the appendix. No shorts, opens or significant reductions in OCL were recorded. As noted earlier, the devices were visually inspected after the stress testing. Some minor incidence of "speckles" were noted on a few of the devices after the IR Reflow. However, the technician was not certain whether the speckles were not present before the test The speckles are an indication of minor delamination, commonly referred to at "pop corn". In this case, it did not cause electrical failure. In future builds, we will look specifically for pop corn on the device surfaces and take microscope photos of the devices before and after stress testing.

Table 2. Embedded Magnetics Reliability Results

| Test Name | Results |
|---|---|
| Thermal Cycling | No mechanical or visual defects found.<br>No abnormal shift in OCL |
| Highly Accelerated Stress Test (HAST) | No mechanical or visual defects found.<br>No abnormal shift in OCL |
| Pressure Cook & Humidity | No mechanical or visual defects found.<br>No abnormal shift in OCL |
| Low Temperature Storage | No mechanical or visual defects found.<br>No abnormal shift in OCL |
| High temperature Storage | No mechanical or visual defects found.<br>No abnormal shift in OCL |
| Solder Reflow | No mechanical or visual defects found.<br>No abnormal shift in OCL |
| Hipot | No failures at 1500 Vrms, 60 seconds. |

## Conclusion

This early data indicates that the PCB construction is reliable for fabricating embedded magnetics. As this point, the technology is too new to have accumulated failure-in-time (FIT) data and determine part-per million (ppm) failure rates As the technology evolves, so will the design rules and process steps. This will be guided by further collection of reliability data and failure categorization. Failures will be linked to different process steps and refinements will be made accordingly.

## Appendix A,

OCL Data for Thermal Cycle, HAST and IR Reflow. Units are in uH.

1. Thermal Shock Test

Remark :-40 to +100C, 100 cycles, each extreme 20 minutes

10cycles

| PN : | AA17 | AC07 | BC07 | BC08 | CD11 | CE11 | DC01 | DC06 | EA10 | EC06 |
|---|---|---|---|---|---|---|---|---|---|---|
| Chan 1 | 268.8 | 178.6 | 182 | 162.1 | 233 | 150.1 | 234 | 232.2 | 274.2 | 133.3 |
| Chan 2 | 267.9 | 178.9 | 185 | 161.8 | 233.2 | 150.1 | 233 | 226 | 245.6 | 200.7 |
| Chan 3 | 276.2 | 164.3 | 183.2 | 179.5 | 260.4 | 149.8 | 223.7 | 241.4 | 245.3 | 166.8 |
| Chan 4 | 277.9 | 164.6 | 183.7 | 180.3 | 260 | 163.6 | 224.2 | 242.7 | 223.4 | 147.2 |

(before data)

| PN : | AA17 | AC07 | BC07 | BC08 | CD11 | CE01 | DC01 | DC06 | EA10 | EC03 |
|---|---|---|---|---|---|---|---|---|---|---|
| Chan 1 | 248.9 | 175 | 212.6 | 159.4 | 197.11 | 148 | 213 | 191.9 | 226.1 | 142.4 |
| Chan 2 | 248.9 | 174.8 | 180.5 | 159.1 | 176.3 | 126.7 | 214 | 198.7 | 217.3 | 201.2 |
| Chan 3 | 264.6 | 165.6 | 183.2 | 176 | 199.1 | 142 | 224.4 | 191.2 | 216.7 | 168.5 |
| Chan 4 | 265.1 | 176.4 | 174.3 | 225.6 | 203.1 | 142 | 224 | 207.1 | 198.5 | open |

100cycles

| PN : | AA17 | AC07 | BC07 | BC08 | CD11 | CE01 | DC01 | DC06 | EA10 | EC06 |
|---|---|---|---|---|---|---|---|---|---|---|
| Chan 1 | 256.4 | 172.4 | 176.6 | 148.7 | 215.9 | 140.9 | 233.6 | 258.1 | 275.4 | 134.7 |
| Chan 2 | 257.6 | 172.9 | 175.9 | 147.4 | 214.6 | 139.8 | 232.2 | 247 | 275.1 | 192.8 |
| Chan 3 | 267 | 151.4 | 170.6 | 166.7 | 236.2 | 138.8 | 226 | 236.2 | 222.8 | 158.4 |
| Chan 4 | 265 | 169.6 | 148.1 | 196.5 | 236.8 | 156 | 252.7 | 253.5 | 222 | 158.3 |

2. Highly Accelerated Stress Test (HAST)

Remark :+85C, 85% RH 50Hrs, 100Hrs, 200 Hrs, OCL 100kHz, 0 bias

| 50 Hrs, P/N | AD04 | AD11 | BC19 | BD01 | CE03 | DD02 | DD09 | EC17 | ED02 | EC05 |
|---|---|---|---|---|---|---|---|---|---|---|
| Chan 1 | 230.4 | 230.7 | 198.1 | 175.3 | 167.3 | 289.2 | 238.1 | 205.8 | 165.2 | 230.5 |
| Chan 2 | 192.8 | 209.5 | 191.6 | 198.1 | 174.1 | 217.1 | 250 | 198.4 | 188.1 | 206.5 |
| Chan 3 | 194.5 | 221.7 | 197.3 | 162.1 | 199.9 | 200.8 | 248.1 | 190.6 | 196.8 | 222 |
| Chan 4 | 203.4 | 208.7 | 196.8 | 161.5 | 153.3 | 196.7 | 362.3 | 200.2 | 175.4 | 212.4 |

(before data)

| 0 Hrs, P/N | AD11 | AD04 | BC19 | BD01 | CE03 | DD02 | DD09 | EC17 | ED02 | EC05 |
|---|---|---|---|---|---|---|---|---|---|---|
| Chan 1 | 223.5 | 203.2 | 177.2 | 149 | 158.2 | 229.8 | 194.4 | 164.4 | 165.5 | 177.2 |
| Chan 2 | 190.6 | 178.3 | 171 | 173.1 | 142.9 | 171.1 | 257.7 | 160.3 | 28.2 | 176 |
| Chan 3 | 198.6 | 177.5 | 169.1 | 137.5 | 165.3 | 158.3 | 198.4 | 157.9 | 173.2 | 187.5 |
|  | 196.5 | 183.3 | 169.9 | 145.5 | 117.5 | 164.5 | 260.7 | 167 | 177.5 | 183.3 |

| 100 Hrs, P/N | AD04 | AD11 | BC19 | BD01 | CE03 | DD02 | DD09 | EC17 | ED02 | EC05 |
|---|---|---|---|---|---|---|---|---|---|---|
| Chan 1 | 228.4 | 237 | 197.6 | 177.1 | 169.2 | 284.9 | 245.1 | 209 | 166 | 232.5 |
| Chan 2 | 191.3 | 208.7 | 191.9 | 198.4 | 172.6 | 216.9 | 247.6 | 196 | 29 | 203.3 |
| Chan 3 | 196.8 | 217 | 197.7 | 161.7 | 197.9 | 199.9 | 249.6 | 186.6 | 189.8 | 221.6 |
| Chan 4 | 201.4 | 205.4 | 193.3 | 163.8 | 149.6 | 195.2 | 359 | 201.2 | 174 | 210.2 |

| 200 Hrs, P/N | AD04 | AD11 | BC19 | BD01 | CE03 | DD02 | DD09 | EC17 | ED02 | EC05 |
|---|---|---|---|---|---|---|---|---|---|---|
| Chan 1 | 218.5 | 235.8 | 199.1 | 175.4 | 166.6 | 294.2 | 247.6 | 205.7 | 165.6 | 231 |
| Chan 2 | 190.6 | 212 | 199.6 | 202.2 | 179 | 220.9 | 248.9 | 198.9 | 28.9 | 205.4 |
| Chan 3 | 199.9 | 211.1 | 204.8 | 165.8 | 203.4 | 205.1 | 253.6 | 190 | 194.6 | 222.7 |
| Chan 4 | 294.4 | 207 | 197.6 | 163.8 | 156.7 | 194.1 | 371.4 | 200.6 | 175.4 | 211.3 |

5. Solder IR Reflow

Remark : Max temp 265℃, duration 20sec(255℃~265℃)., OCL 100kHz, 0 bias

| 1st pass, P/N | AE04 | AE06 | BE07 | BE14 | CE16 | DE07 | DE09 | EE12 | EE13 |
|---|---|---|---|---|---|---|---|---|---|
| Chan 1 | 164 | 226 | 174 | 185 | 253 | 274 | 212 | 148.8 | 163 |
| Chan 2 | 163 | 226 | 174 | 185 | 248 | 285 | 209.9 | 210 | 148.2 |
| Chan 3 | 209 | 164 | 175 | 234 | 229 | 282 | 230 | 200 | 148 |
| Chan 4 | 217 | 211 | 262 | 273 | 240 | 281 | 232 | 201 | 165 |

(before data)

| PN : | AE04 | AE06 | BE07 | BE14 | CE16 | DE07 | DE09 | EE12 | EE13 |
|---|---|---|---|---|---|---|---|---|---|
| Chan 1 | 130.4 | 123.6 | 129.4 | 115.3 | 158.7 | 166.5 | 143.2 | 102.5 | 129.3 |
| Chan 2 | 130.2 | 123.5 | 129.6 | 114.7 | 158 | 148.5 | 142.5 | 123.4 | 109.2 |
| Chan 3 | 130.8 | 131.5 | 123.9 | 137.3 | 136.3 | 149.5 | 133.7 | 117.7 | 109.3 |
| Chan 4 | 139.2 | 124.3 | 152.1 | 163.5 | 132.2 | 170 | 134.5 | 123.5 | 118.3 |

| 2nd pass, P/N | AE04 | AE06 | BE07 | BE14 | CE16 | DE07 | DE09 | EE12 | EE13 |
|---|---|---|---|---|---|---|---|---|---|
| Chan 1 | 169.9 | 193.8 | 247.2 | 251.2 | 258.7 | 255.5 | 216.9 | 158.4 | 167.7 |
| Chan 2 | 164 | 223.9 | 167.6 | 199.8 | 219 | 250.5 | 215.6 | 101.8 | 161.3 |
| Chan 3 | 205.9 | 158 | 173.9 | 224.6 | 214.2 | 250.3 | 209.7 | 18.3 | 160.4 |
| Chan 4 | 164 | 222.5 | 168 | 199.4 | 232.8 | 267.2 | 209.8 | 203.6 | 176.2 |

| 3rd pass, P/N | AE04 | AE06 | BE07 | BE14 | CE16 | DE07 | DE09 | EE12 | EE13 |
|---|---|---|---|---|---|---|---|---|---|
| Chan 1 | 116.6 | 196.3 | 253.7 | 244.6 | 247.7 | 261.6 | 215.6 | 154.5 | 170.7 |
| Chan 2 | 168.1 | 221.1 | 177.6 | 202.7 | 224.3 | 251.4 | 214 | 211 | 152.9 |
| Chan 3 | 210.5 | 158.5 | 173.1 | 234.8 | 211.4 | 251.1 | 217.8 | 174.7 | 151.2 |
| Chan 4 | 168.1 | 218.2 | 178.4 | 201.5 | 239.1 | 278.3 | 219.7 | 211.9 | 175.8 |