ALMA Future Science Development Program Workshop (24-25 Aug 2016)

ALMA Band 2 Prototype Project
Kamaljeet S Saini

NA Development Cycle 2
ALMA Band 2 plus Prototype Project
Kamaljeet S Saini

represents 67-95 GHz
enhanced frequency coverage
ALMA Band 2 Prototype Project

Outline / Overview

1. Why build a Band 2 prototype?
2. Configuration of the Band 2 prototype receiver.
4. Remaining work before we can move to propose a full build out for Band 2.
5. Outline of future plan to get to implementation/construction phase.
ALMA Band 2 Prototype Project

Science Case

Band 2 is the one frequency band in the baseline ALMA design which remains to be completed. Primary objectives include:

- To cover the largely unexplored 4 mm band, previously available only on the 12 m Kitt Peak telescope (ARO) and very recently on the GBT (NRAO).
- Access the $J = 1 \rightarrow 0$ transitions of the deuterium analogs of common, abundant interstellar molecules, including $\text{DCO}^+$, $\text{DCN}$, $\text{N}_2\text{D}^+$ & $\text{C}_2\text{D}$, as well as $\text{H}_2^{13}\text{CO}$, $^{13}\text{C}_2\text{H}$, $\text{H}^{13}\text{CO}^+$, $\text{HC}^{18}\text{O}$, $\text{H}^{13}\text{CN}$, $\text{HC}^{15}\text{N}$, $\text{H}_2\text{CO}$, $\text{HCNH}^+$ and $\text{C}_2\text{H}$.
- “Cold chemistry”, using the lowest energy transitions of simple deuterated species to trace the coldest and densest areas of star-forming cores and proto-planetary disks.
- Study galaxies and clusters at low intermediate redshifts – this is currently unavailable with the present ALMA bands for the important CO($1 \rightarrow 0$), HCN($1 \rightarrow 0$), HCO$^+$(1 $\rightarrow$ 0), HNC($1 \rightarrow 0$), and SiO(2 $\rightarrow$ 1) transitions.
ALMA Band 2 Prototype Project

Valuable to cover spectral lines up to ~ 95 GHz. Band 2+ ?

Band 2

Band 3

Transmission Fraction

Frequency [GHz]

D$_3$CO$^+$

DCO$^+$/D$_2$C$^+$

DNC

N$_2$O$^+$

N$_2$H$^+$

H$_2$CO$^+$

HNC

N$_2$D

N$_2$D

N$_2$D

Band 2+
ALMA Band 2 Prototype Project

Team Members / Contributors

• Low Noise Amplifiers:
  – Marian Pospieszalski (MIC)
  – Kieran Cleary & Team at CRAL (MMIC)
  – Matthew Morgan

• Optics:
  – Sri Srikanth
  – Alvaro Gonzalez

• Down Converter:
  – Dustin Vaselaar
  – Jim Muehlberg
  – Matthew Morgan
  – Kamaljeet Saini

• Local Oscillator:
  – Dustin Vaselaar
  – Jim Muehlberg
  – Kamaljeet Saini

• Cold Cartridge:
  – Kirk Crady
  – Greg Morris
  – Arthur Symmes

• Shop & Chemistry Lab:
  – Greg Morris
  – Gerry Petencin

• Evaluation / Metrology:
  – John Effland
  – Morgan McLeod
  – Kirk Crady
  – John Buchanan
  – Kamaljeet Saini

• Consultancy & Support:
  – Matthew Morgan
  – S K Pan
  – Robert Dickman
ALMA Band 2 Prototype Project

Project Summary - I

• The first ALMA Band 2 receiver (cold cartridge, local oscillator, as well as IF down converter) has been constructed.

• Even at the outset, the two year development project timeline was very tight to develop (design, fabricate and construct) MMIC based LNAs and then construct the receiver in a serial fashion.

• Consequently, we have constructed the receiver prototype around NRAO/CDL MIC (chip and wire) E-band LNAs in parallel with the CRAL MMIC effort, which is now beginning to produce results. Receiver will be upgraded with MMIC LNAs when they are delivered in September 2016.

• This presentation provides an overview of important cartridge component performances, cartridge (cold and warm) construction and alignment details, and significant receiver performance metrics (but not comprehensive compliance data, which has been taken and incorporated into the design report).
ALMA Band 2 Prototype Project
Project Summary - II

• Test results indicate that even the state-of-the-art E-band MIC LNAs barely meet the overall ALMA Band 2 noise specification by themselves. Allowing for additional noise degradation from the optics, it will be difficult to meet the existing ALMA noise specification by using them. Recent MMIC results appear promising (their noise temperature averaged over 67-90 GHz is ~10 K better compared to MIC amplifier average noise performance) and the receiver will be upgraded with MMIC LNAs when they are received in September 2016.

• The optics specifications are generally met with the exception that there are dips in polarization efficiency at specific frequencies that fall below the 99.5% specification value. These are attributed (both by measurements as well as by simulations) to an interaction of the 15 K IR filters with the horn aperture – an effect also seen on some other ALMA bands. (Discussing proposal to remove 15 K IR filters for both Band 1 and 2 to address this issue).
ALMA Band 2 Receiver Prototype

Block Diagram

**Interfaces**
- **ICD1**: Cold Cartridge Assembly to ALMA Cryostat
- **ICD2**: Cold Cartridge Assembly to Warm Cartridge Assembly
- **ICD3**: Cold Cartridge Assembly to Bias Module
- **ICD4**: FE LO to BE Photonics LO
- **ICD5**: Cold Cartridge Assembly to IF Switch Subsystem
- **ICD6**: Warm Cartridge Assembly to Harness Plate
- **ICD7**: Cartridge Bias Module 40.04.02
- **ICD8**: Warm Cartridge Assembly 40.10.02

**Specifications**
- **RF**: 67 – 90 GHz
- **LO**: 73.6 – 88.3 GHz
- **USB IF**: 12.27 – 14.72 GHz

**Equipment**
- **Amplifier Bias**
- **Warm Cartridge Assembly**
- **Cold Cartridge Assembly**
- **Frequency Tripler**
- **Photo Mixer**
- **Phase Locked Loop**
- **MCDPLL**
- **AMC**
- **Warm IF Amplifiers**
- **Pol-0 & Pol-1**
- **Pol-0**
- **Pol-1**
- **IF Outputs 4 – 12 GHz**
- **Power Amplifier Drain Bias**
- **MCDPLL**
- **2SB Processor**
- **LO M&C**
- **Frequency Doublwer**
- **YTO**

**ALMA Future Science Development Program Workshop (24-25 Aug 2016)**
ALMA Band 2 Cold Cartridge Prototype

- Feedhorn
- Ortho-mode transducer
- Low Noise Amplifier(s)
- Thermal links to 15 K stage
- Thermal anchors
- 15 K Stage
- 110 K Stage
- 300 K Baseplate
ALMA Band 2 Warm Cartridge Prototype (Down Converter & Local Oscillator)

- IF amplifiers
- 90° IF hybrid(s)
- RF input from cold cartridge
- YIG Tuned Oscillator
- Active Multiplier Chain and Power amplifier
- Heatsink
ALMA Band 2 Receiver Prototype Evaluation in the ALMA Cryostat

- Environmental Chamber HVAC
- Tilt Table
- Front-End Support Structure (FESS)
- Test Cryostat
- Front-End Electronics Chassis
- NSI Beam Scanner
- FETMS Equipment Racks
ALMA Band 2 Receiver Prototype
System Noise Temperature Estimation

<table>
<thead>
<tr>
<th>Band 2 Receiver stage</th>
<th>Gain</th>
<th>Cumulative Gain to preceding stage</th>
<th>Noise Figure</th>
<th>Noise Temperature</th>
<th>$T_{\text{equivalent}}$ (for MIC based)</th>
<th>$T_{\text{equivalent}}$ (for MMIC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens/Window (room temperature)</td>
<td>-0.1 dB</td>
<td>0.0 dB</td>
<td>0.1 dB</td>
<td>8.9 K</td>
<td>8.9 K</td>
<td>8.9 K</td>
</tr>
<tr>
<td>IR Filters (15 K and 80 K)</td>
<td>-0.1 dB</td>
<td>-0.1 dB</td>
<td>0.1 dB</td>
<td>1.4 K</td>
<td>1.5 K</td>
<td>8.9 K</td>
</tr>
<tr>
<td>Feedhorn (15 K)</td>
<td>-0.1 dB</td>
<td>-0.3 dB</td>
<td>0.1 dB</td>
<td>0.3 K</td>
<td>0.4 K</td>
<td>1.5 K</td>
</tr>
<tr>
<td>OMT</td>
<td>-0.1 dB</td>
<td>-0.4 dB</td>
<td>0.1 dB</td>
<td>0.3 K</td>
<td>0.4 K</td>
<td>8.9 K</td>
</tr>
<tr>
<td>E-Band Amplifier (15 K)</td>
<td>35.0 dB</td>
<td>-0.5 dB</td>
<td><strong>36.5 K</strong></td>
<td><strong>36.5 K</strong></td>
<td>40.6 K</td>
<td>29.2 K</td>
</tr>
<tr>
<td>Waveguides, feed-thru and BPF</td>
<td>-4.0 dB</td>
<td>34.5 dB</td>
<td>4.0 dB</td>
<td>453.6 K</td>
<td>0.2 K</td>
<td>0.2 K</td>
</tr>
<tr>
<td>E-Band Amplifier (room temperature)</td>
<td>14.0 dB</td>
<td>30.5 dB</td>
<td>3.5 dB</td>
<td>371.6 K</td>
<td>0.3 K</td>
<td>0.3 K</td>
</tr>
<tr>
<td>2 SB Downconverter</td>
<td>-12.0 dB</td>
<td>44.5 dB</td>
<td>12.0 dB</td>
<td>4445.7 K</td>
<td>0.2 K</td>
<td>0.2 K</td>
</tr>
<tr>
<td>Warm IF Amplifier</td>
<td>30.0 dB</td>
<td>32.5 dB</td>
<td>2.0 dB</td>
<td>175.5 K</td>
<td>0.1 K</td>
<td>0.1 K</td>
</tr>
<tr>
<td>Total</td>
<td>62.5 dB</td>
<td></td>
<td></td>
<td></td>
<td>52.4 K</td>
<td>41.1 K</td>
</tr>
</tbody>
</table>

Average = 36.5 K
ALMA Band 2 Receiver Prototype
Thermal Budget(s)

From ALMA Front End Thermal Budget, FEND-40.00.00.00-050-B-GEN:

<table>
<thead>
<tr>
<th>15 K Stage</th>
<th>Bands 1 - 2</th>
<th>Band 3</th>
<th>Bands 4 - 8 - 10</th>
<th>Band 6</th>
<th>Band 7</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive heat load</td>
<td>95 mW</td>
<td>95 mW</td>
<td>95 mW</td>
<td>75 mW</td>
<td>115 mW</td>
<td>950 mW</td>
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<tr>
<td>Active heat load</td>
<td>90 mW</td>
<td>20 mW</td>
<td>67 mW</td>
<td>67 mW</td>
<td>15 mW</td>
<td>200 mW</td>
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<tr>
<td>Total heat load</td>
<td>185 mW</td>
<td>115 mW</td>
<td>162 mW</td>
<td>162 mW</td>
<td>130 mW</td>
<td>1150 mW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>110 K Stage</th>
<th>Bands 1 - 2</th>
<th>Band 3</th>
<th>Bands 4 - 8</th>
<th>Bands 9 - 10</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive heat load</td>
<td>450 mW</td>
<td>350 mW</td>
<td>700 mW</td>
<td>600 mW</td>
<td>5950 mW</td>
</tr>
<tr>
<td>Active heat load</td>
<td>150 mW</td>
<td>50 mW</td>
<td>150 mW</td>
<td>250 mW</td>
<td>550 mW</td>
</tr>
<tr>
<td>Total heat load</td>
<td>600 mW</td>
<td>400 mW</td>
<td>850 mW</td>
<td>850 mW</td>
<td>6500 mW</td>
</tr>
</tbody>
</table>

• Requirements met comfortably for 15 K stage, CLNAs dissipate 15-30 mW each (article to article variation, depends on optimization).
• No active component on the 110 K stage.
ALMA Band 2 Cold Cartridge Prototype
Mechanical Analysis

A mechanical design analysis was performed by employing the Finite Element Analysis (FEA) technique using the NX NAStRAN version (with FEmap) provided by Siemens.

Temperature distributions, stresses, & deflections (both gravity and temperature induced), and vibrational modes and frequencies calculated.

Band 2 Cold Cartridge Assembly
FEA Model showing mesh density
ALMA Band 2 Cold Cartridge Prototype

Optics Design

• Frequency independent illumination taper of -12 dB requires a 106 mm diameter, 785 mm long horn. Will result in beam truncation due to limited cryostat aperture – dictated by decisions made at the time of cryostat design. Similar truncation constraints apply to cooled lens.

• Reflective optics has to be placed outside the cartridge/cryostat (due to space constraints). Limited space outside due to calibration device, experimental design increased angle of incidence on the subreflector and yielded poorer polarization performance.

• Moderate beam waist horn with refractive optics (lens, which also serves as the vacuum window) design option was chosen.

• HDPE was selected for the lens material. Alternatives like high dielectric constant Si were studied (to save losses, since the lens would be thinner), but were not selected as the loss was found to be similar to a thicker HDPE lens. (Loss depends on electrical thickness, not the physical thickness) – some renewed interest in this regard and reviewing it again with help from NAOJ who have the expertise to fabricate matching layer on Si material. Relatively easy to substitute an alternate lens later to pick up improvement in noise temperature.
ALMA Band 2 Cold Cartridge Prototype
Horn & Lens

<table>
<thead>
<tr>
<th>Lens #</th>
<th>Illumination taper at 3.6° (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>67 GHz</td>
</tr>
<tr>
<td>2</td>
<td>-13.44</td>
</tr>
<tr>
<td>3</td>
<td>-14.37</td>
</tr>
<tr>
<td>4 (Fresnel, 1-zone)</td>
<td>-10.88</td>
</tr>
</tbody>
</table>
ALMA Band 2 Cold Cartridge Prototype
Orthomode Transducer
ALMA Band 2 Cold Cartridge Prototype
Location of the Band 2 window on the ALMA cryostat

Need 2.48° tilt towards the center of the cryostat
Location of center of the lens can be measured from an arbitrary (fixed) fiduciary mark on the cryostat using a beam-scanner mounted red laser → Can adjust lens position by a given (delta) amount from existing position, to get desired beam pointing.
ALMA Band 2 Receiver Prototype
Optics Performance / Beam Pointing

Band 2 Pointing Angles, RF 82 GHz, tilt 45 deg

<table>
<thead>
<tr>
<th>RF GHz</th>
<th>pol</th>
<th>Elevation</th>
<th>AZ Center</th>
<th>EL Center</th>
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</thead>
<tbody>
<tr>
<td>82</td>
<td>0</td>
<td>45</td>
<td>-1.7718</td>
<td>1.8484</td>
</tr>
<tr>
<td>82</td>
<td>1</td>
<td>45</td>
<td>-1.7624</td>
<td>1.7619</td>
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</table>

<table>
<thead>
<tr>
<th>RF GHz</th>
<th>Elevation</th>
<th>Squint (%FBPW)</th>
<th>squint (arc seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>82</td>
<td>45</td>
<td>1.37</td>
<td>0.99</td>
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</tbody>
</table>
ALMA Band 2 Receiver Prototype
Optics Performance / Beam Pointing
ALMA Band 2 Receiver Prototype

Optics Performance / Beam Patterns
ALMA Band 2 Receiver Prototype
Optics Performance / Beam Efficiencies

Band 2 Optics Efficiencies
Pol 0

- Spillover
- Total Aper
- Taper
- Spec: Overall
- Phase (Rt Axis)
- Pol (Rt Axis)
- Spec: Pol (Rt Axis)
- Pol Meas May 2105

Efficiency vs. Freq (GHz)
65 70 75 80 85 90
75% 80% 85% 90% 95% 100%

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ALMA Band 2 Receiver Prototype
Optics Performance / Beam Efficiencies

Measured polarization efficiency of feed horn & lens with and without the 15 K IR filter (anechoic chamber measurements).
ALMA Band 2 Warm Cartridge Prototype
RF 90° Hybrids
## ALMA Band 2 Warm Cartridge Prototype

### 2SB Downconverter / Image Rejection

<table>
<thead>
<tr>
<th>LO (GHz)</th>
<th>RF</th>
<th>RF</th>
<th>RF</th>
<th>RF</th>
<th>RF</th>
<th>RF</th>
<th>RF</th>
<th>RF</th>
<th>IR</th>
<th>IR</th>
<th>IR</th>
<th>IR</th>
<th>IR</th>
<th>IR</th>
<th>IR</th>
<th>IR</th>
<th>IR</th>
<th>IR</th>
<th>(USB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>72</td>
<td>67</td>
<td>68</td>
<td>69</td>
<td>70</td>
<td>71</td>
<td>72</td>
<td>73</td>
<td>74</td>
<td>14.5</td>
<td>No meas</td>
<td>67</td>
<td>70</td>
<td>71</td>
<td>72</td>
<td>73</td>
<td>74</td>
<td>75</td>
<td>76</td>
<td>80</td>
</tr>
<tr>
<td>74</td>
<td>67</td>
<td>68</td>
<td>69</td>
<td>70</td>
<td>71</td>
<td>72</td>
<td>73</td>
<td>74</td>
<td>14.2</td>
<td>17.5</td>
<td>20.4</td>
<td>No meas</td>
<td>67</td>
<td>70</td>
<td>71</td>
<td>72</td>
<td>73</td>
<td>74</td>
<td>75</td>
</tr>
<tr>
<td>76</td>
<td>67</td>
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<td>69</td>
<td>70</td>
<td>71</td>
<td>72</td>
<td>73</td>
<td>74</td>
<td>10.6</td>
<td>15.2</td>
<td>19.5</td>
<td>15.1</td>
<td>No meas</td>
<td>67</td>
<td>70</td>
<td>71</td>
<td>72</td>
<td>73</td>
<td>74</td>
</tr>
<tr>
<td>78</td>
<td>67</td>
<td>68</td>
<td>69</td>
<td>70</td>
<td>71</td>
<td>72</td>
<td>73</td>
<td>74</td>
<td>7.6</td>
<td>10.0</td>
<td>10.9</td>
<td>11.4</td>
<td>11.4</td>
<td>No meas</td>
<td>67</td>
<td>70</td>
<td>71</td>
<td>72</td>
<td>73</td>
</tr>
<tr>
<td>80</td>
<td>68</td>
<td>69</td>
<td>70</td>
<td>71</td>
<td>72</td>
<td>73</td>
<td>74</td>
<td>75</td>
<td>11.4</td>
<td>13.9</td>
<td>23.4</td>
<td>13.9</td>
<td>15.1</td>
<td>20.2</td>
<td>24.1</td>
<td>26.4</td>
<td>30.1</td>
<td>34.0</td>
<td>39.0</td>
</tr>
</tbody>
</table>

Number in green and blue font represent image rejection values corresponding to lower and upper sidebands respectively. Specification is better than 10 dB IR over 80% of the IF range, and better than 7 dB IR over the full range. Intermediate frequencies outside of the contiguous diamond shaped area correspond to RFs that are “in-band” but have out-of-band image falling on it. “Out-of-band” RFs that are of interest are shown grayed out.
ALMA Band 2 Receiver Prototype
Noise Temperature (Polarization-0)

**Average ~ 51.2 K**

![Graph showing noise temperature vs RF (GHz)]

- ** Specification**
  - ~10 hf/k criteria
  - ~6 hf/k criteria (80% band)

<table>
<thead>
<tr>
<th>Band 2 Receiver stage</th>
<th>Gain</th>
<th>Cumulative Gain to preceding stage</th>
<th>Noise Figure</th>
<th>Noise Temperature</th>
<th>$T_{equivalent}$ (for NBR band)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens/Window (asном temperature)</td>
<td>-0.1 dB</td>
<td>0.0 dB</td>
<td>0.1 dB</td>
<td>8.9 K</td>
<td>8.0 K</td>
</tr>
<tr>
<td>EE Filters (15 K bandwidth)</td>
<td>-0.1 dB</td>
<td>-0.1 dB</td>
<td>0.1 dB</td>
<td>1.4 K</td>
<td>1.5 K</td>
</tr>
<tr>
<td>Feedhorn (15 K)</td>
<td>-0.1 dB</td>
<td>-0.3 dB</td>
<td>0.1 dB</td>
<td>0.3 K</td>
<td>0.4 K</td>
</tr>
<tr>
<td>DMT</td>
<td>-0.1 dB</td>
<td>-0.4 dB</td>
<td>0.1 dB</td>
<td>0.4 K</td>
<td>0.4 K</td>
</tr>
<tr>
<td>L-band Amplifier (15 K)</td>
<td>35.0 dB</td>
<td>35.5 dB</td>
<td>35.5 K</td>
<td>55.5 K</td>
<td>85.0 K</td>
</tr>
<tr>
<td>Waveguides, feed-thru and BPF</td>
<td>-4.0 dB</td>
<td>31.5 dB</td>
<td>40.0 dB</td>
<td>49.0 K</td>
<td>52.1 K</td>
</tr>
<tr>
<td>L-band Amplifier (noise temperature)</td>
<td>14.0 dB</td>
<td>30.5 dB</td>
<td>19.5 dB</td>
<td>31.0 K</td>
<td>28.1 K</td>
</tr>
<tr>
<td>2K Band downconverter</td>
<td>-12.0 dB</td>
<td>44.5 dB</td>
<td>32.0 dB</td>
<td>46.5 K</td>
<td>52.1 K</td>
</tr>
<tr>
<td>Warm IR Amplifier</td>
<td>20.0 dB</td>
<td>32.5 dB</td>
<td>20.0 dB</td>
<td>17.5 K</td>
<td>20.2 K</td>
</tr>
<tr>
<td>Total</td>
<td>0.0 dB</td>
<td>32.5 dB</td>
<td>2.0 dB</td>
<td>17.5 K</td>
<td>20.2 K</td>
</tr>
</tbody>
</table>

**Band 2 57–90 GHz**
ALMA Band 2 Receiver Prototype
Interaction between 15 K IR filters and CLNA input

Measured reflection coefficient of the OMT plus feed horn without IR filter (trace labeled “omtfd”) and that of the OMT plus feed horn with the 15 K IR filter placed 5 mm from the feed horn aperture (trace labeled “15K5mm”)
ALMA Band 2 Prototype Project

Status of the CRAL MMIC effort

• First wafer run (NGC) with multiple Band 2 LNA MMIC design variants completed in December 2015.

• All four wafers were successful, with good yields (room temperature testing completed on all wafers).

• Cryogenic probing of one wafer at CRAL indicates that there are several promising design variants for Band 2 application.

• Subsequently, these were packaged into test blocks to qualify their performance, and to identify designs that could be used for Band 2 multi-stage amplifier for integration into the prototype cartridge.

• Once the performance is confirmed, proceed to pick the corresponding chips from the NGC wafers and store for the full construction phase.
ALMA Band 2 Prototype Project
Preliminary packaged MMIC cryogenic performance

CLNA Noise Temperature

Noise Temperature (K)

Frequency (GHz)

E-001 MIC
90LN2A MMIC

(Packaged amplifier data, single MMIC)
ALMA Band 2 Prototype Project

2-stage packaged MMIC LNA cryogenic performance

Minimum Tdut with Associated Gain

Bias optimized for lowest noise

Minimum Tdut with Associated Gain

Bias optimized for lowest noise for gain >35 dB

(Packaged amplifier data)
ALMA Band 2\textsuperscript{plus} Prototype Project

Final year plan. Next Steps . . .

• Finish evaluation with CRAL MMIC based amplifiers and update relevant project documentation as well as test reports.

• Review Band 2+ Noise Specifications.

• Preliminary Design Review.

• Propose a phased build-out for Band 2+ under the upcoming NA Development Project Call in October 2016.

• Questions.