The Effect of Strong RFI on Astronomical Imaging Arrays

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There’s Bad Stuff Out There!

- Science requirements drive the design of new radio telescopes to wide bandwidths – 2:1 BWR.
- This obviously increases the vulnerability of these systems to high-power man-made emissions.
- These signals can easily exceed the total system noise power.
- DME signals provide a good example – peak pulse from 100 km distance exceeds $kT\Delta v$ by 20dB!
- Clearly, high linearity in signal processing chain is needed.
But What If…

• But linearity sufficient to prevent significant amplifier compression for all conceivable signals is not possible.

• Some will get through, and cause significant gain compression.

• What happens to imaging performance for frequencies not directly ‘wiped out’ by the RFI?

• We report here on two attempts to measure the effect, and describe a third experiment (in planning) which we hope will answer the question.
Voltage Relationship

- Showing a generic voltage transfer relation.
Defining Amplifier Compression

- The VLA’s C-band FE approximate response.
Harmonic Distortion

• To understand the process, some simple analysis is needed.

• In general, (presuming no hysteresis), the voltage transfer function can be written as:

\[ V_{\text{out}} = G_v V_{\text{in}} (1 + \alpha V_{\text{in}} + \beta V_{\text{in}}^2 + \ldots) \]

• Because the voltage transfer curve is an odd function, \( \alpha \sim 0 \), and we need only consider the odd terms.

• We can then easily analyze the output harmonic content from a two-frequency input given by:

\[ V_{\text{in}} = A \cos(\omega_1 t + \phi_1) + B \cos(\omega_2 t + \phi_2) \]
Harmonic Amplitudes
(assuming A >> B)

- The amplitude in the fundamental is reduced by $3\beta A^2B/2$.
- Harmonics are produced which put power outside the passband. (Yellow)
- Two harmonic combinations fold spectral information back into the passband. (Red/Orange)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Linear</th>
<th>Cubic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_1$</td>
<td>A</td>
<td>$3\beta A^{3/4}$</td>
</tr>
<tr>
<td>$\omega_2$</td>
<td>B</td>
<td>$3\beta A^2B/2$</td>
</tr>
<tr>
<td>$3\omega_1$</td>
<td>--</td>
<td>$\beta A^{3/4}$</td>
</tr>
<tr>
<td>$3\omega_2$</td>
<td>--</td>
<td>$\beta B^{3/4}$</td>
</tr>
<tr>
<td>$2\omega_1 + \omega_2$</td>
<td>--</td>
<td>$3\beta A^2B/4$</td>
</tr>
<tr>
<td>$\omega_1 + 2\omega_2$</td>
<td>--</td>
<td>$3\beta AB^{2/4}$</td>
</tr>
<tr>
<td>$2\omega_1 - \omega_2$</td>
<td>--</td>
<td>$3\beta A^2B/4$</td>
</tr>
<tr>
<td>$2\omega_2 - \omega_1$</td>
<td>--</td>
<td>$3\beta AB^{2/4}$</td>
</tr>
</tbody>
</table>
Spectral Folding

- Two cubic terms fold spectral information back – one is especially strong.
  - A represents the RFI amplitude.
  - B gives the fundamental response.
  - Red shows the reflected, inverted stronger response.
  - Green shows the weaker, broader reflection.
What should we see?

• A reduction in the output amplitude.
  – We expect this will lower the SNR as the effective gain is reduced.
  – An alternative interpretation (B.Clark) is that the amplifier is effectively turned off when highly saturated, so the SNR drops as: \( \sqrt{f_{ON}} \)

• A ‘mixing’ of spectral information.
  – Spectral lines will appear in wrong places.
  – ‘Closure’ errors may occur, degrading imaging performance.

• This analysis is too rough to make quantitative predictions – we need to measure these effects.
First Experiment

• In the first and simplest experiment, we simply turned on the VLA’s `Solar Cals’.
• This raises the operating point by about 13 dB, which is well short of even the 1% compression point.
• Not surprisingly, no effect on imaging was found.
• Details in EVLA Memo #66.
2nd Experiment

- In this attempt, we added a strong CW tone to the first-stage amplifiers.
- Expected to be a much better model of a real RFI signal.
- The tone power was set to drive the RCP side to 1 dB compression, and the LCP side to 6 dB compression.
- A filter was inserted to prevent the tone from propagating beyond the first amplifier.
Frequency Setup

Relative Power

Under LO Control

CW Tone “OFF” (2010 MHz)

CW Tone “ON” (4010 MHz)

Tone Select Filter 3750/630 MHz

Tone Reject Filter 4850/600 MHz

Gain Compression in Desired Band due to Saturating CW Tone

C-Band LNA Broadband Response

VLA Standard C-Band 4500-5000 MHz
Oops!

- The ‘RFI’ frequency of 4010 MHz lies outside the 4500 – 5000 MHz passband, so the two 3rd order harmonic difference reflections appeared at:
  - 3010 to 3510 MHz: outside the correlated passband, (and blocked by the Tone Reject Filters)
  - 4990 to 5990 MHz: the lower end lies within the passband, but we didn’t correlate at this frequency.
- So the imaging degradation effects we were looking for could not be present (and weren’t!).
- The loss of SNR remains, and we did measure this.
Setup

- Four antennas were modified, with compression levels (in dB) as shown in the table:

<table>
<thead>
<tr>
<th>Ant.</th>
<th>IF ‘A’</th>
<th>IF ‘C’</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.5</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>5.0</td>
<td>0.8</td>
</tr>
<tr>
<td>22</td>
<td>6.0</td>
<td>0.8</td>
</tr>
<tr>
<td>28</td>
<td>6.4</td>
<td>1.1</td>
</tr>
</tbody>
</table>

- Observations made of 3C286 (7.46 Jy, nearly unresolved), for four hours, split equally between 50 MHz continuum (4885 MHz) and 12.5 MHz spectral line (390 kHz spectral resolution).
Results -- Sensitivity

- The loss in sensitivity was measured in two ways:
  - A change in the calibration coefficient
  - Directly measuring the SNR in the correlated data.
- The results were the same for both approaches:
  - A marginal loss (1% +/- 0.5%) in SNR at 1 dB compression
  - A significant loss of 16% in SNR at 6 dB compression.
Results -- Closure

• ‘Closure’ effects (amplitude or phase changes in the correlator product which cannot be factored into antenna-based amplitude or phase) were sought in two ways:
  – Closure error calculation by comparison of observed and predicted visibilities from a standard model.
  – Direct comparison of measured visibilities between the ‘Tone On’ and ‘Tone Off’ states.

• No closure effects were detectable to a level of 0.1%. (Not surprising, but reassuring).
High Precision!

- Showing the accuracy with which we can measure the visibility.
What Next?

• We are planning a third experiment, which we expect will give us an estimate of what we want to know:
  – The leakage and imaging qualities of astronomical information which is ‘reflected back’ within the passband by strong RFI in that passband.

• The idea: To use a tone within L-band to `reflect’ the high end of the band onto the low end.
  – More specifically: To use a tone at ~1555 MHz to make a strong OH maser line at 1665 MHz appear near 1445 MHz.
  – The `reflection coefficient’ and imaging properties will then be easy to directly measure, as a function of tone strength.