Calibration Requirements of the Design Reference Science Plan for ALMA

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Abstract

The Design Reference Science Plan offers a valuable opportunity to assess the calibration requirements for the Atacama Large Millimeter Array, as well as the impact that relaxing these requirements will have on the science that can be achieved. This document summarizes the calibration requirements based on 67% of the projects included in the Design Reference Science Plan for which input was received. The majority of projects can be successfully executed with an *absolute* calibration accuracy of 5%. Stronger requirements are placed on the *repeatability* and the *relative* calibration accuracy (both within a single band and between bands), for which most projects require either 1–3% or 5%. The document discusses a number of key arguments that are offered in support of these requirements. Only a few projects in the Design Reference Science Plan include *polarization* measurements, and no conclusions can be based on their listed requirements of $\sim 10^\circ$ on the angle and 1% on the amplitude.

1 Introduction

The Atacama Large Millimeter Array (ALMA) will revolutionize astronomy at millimeter and sub-millimeter wavelengths with unprecedented sensitivity and resolving power. It will operate at an altitude of 5000 m on the Llano de Chajnantor in the Chilean Andes, where atmospheric transparency and stability is among the most favorable in the world. One of the essential conditions for ALMA to reach its scientific potential is accurate calibration of the measurements at the various operating frequency bands.

Currently, the amplitude calibration goal is 1% at frequencies below 300 GHz and 3% above, which may be very challenging to realize. The ALMA Science Advisory Committee (ASAC) was asked by the ALMA Board to assess the scientific impact of different relative and absolute calibration accuracies. The projects included in the Design Reference Science Plan (DRSP[1]) offer an excellent starting point for this assessment: they cover all likely science topics and observing modes as can be currently foreseen. To find out what calibration requirements are needed by the projects in the DRSP, all DRSP authors were asked to submit answers to a short questionnaire (see Appendix A). They provided the required accuracy (1–3%, 5%, or 10%) of the absolute and relative calibration as well as the repeatability and polarization, together with a short motivation.

2 Results

By August 2004, responses has been received for 85 out of the 127 DRSP projects (67%). The level of response was fairly uniform over the various science topics and observing modes, and the resulting calibration requirements should be representative of the typical use of ALMA. The individual responses are available of the web[2], and are summarized here. Appendix B presents a breakdown of the number of projects per band and observing mode (spectral line or continuum)

[1] More information on the DRSP and links to the individual projects can be found at `http://www.strw.leidenuniv.nl/~alma/drsp.html`

[2] See `www.strw.leidenuniv.nl/~alma/drsp/calib_responses.html`

that require accuracies of 1%, 1–3%, 5%, or 10% for each of the calibration attributes. The figures in Appendix C show the distributions as histograms.

The next two sections first discuss the science arguments that are most often used to motivate the desired calibration accuracy (§2.1), after which the overall calibration requirements are summarized (§2.2).

2.1 Key Science Arguments

- **Absolute Calibration**
  - Requirements on the absolute calibration usually follow from the need to accurately determine the total mass or column density of a tracer. For these determinations as high a calibration accuracy is desired, although 5% is often already sufficient. The most stringent requirements are posed, e.g., by projects that derive the star-formation efficiency or that try and obtain properties of Solar System objects.
  - A few projects require a high accuracy in order to improve on the (low frequency) capabilities of current radio telescopes.
  - The requirements can be relaxed for detection experiments, objects that are expected to be weak (and where sensitivity rather than accuracy is called for), and projects that can use internal calibration (e.g., that use line/continuum ratios).
  - Respondents frequently mention that 10% absolute calibration accuracy suffices because the employed models do not allow more accurate results to be extracted. A higher accuracy, however, may be desired when taking into account the *archival* value of the data.
- **Repeatability**
  - High accuracy on the repeatability is required when (1) the object is expected to be variable, and (2) for combination of the data with observations in other configurations or the Atacama Compact Array, other frequencies (observed at other times), other fields of a survey, or mosaics.
- **Relative Calibration**
  - For continuum observations the spectral slope or shape of the spectral energy distribution is the driver behind high accuracy.
  - For line observations the use of line ratios drives the requirements to high accuracies. A specific case of relative calibration follows from the measurement of line profiles, which require high accuracy narrow-band relative calibration (passband calibration).
  - These motivations are valid both for the relative calibration within a single band and the relative calibration between different bands. For a large fraction of projects, excellent relative calibration seems to be essential to reach the science objectives.
- **Polarization Calibration**
  - Too few projects in the DRSP use polarization measurements to draw any conclusions on the required accuracy.
- **Science Categories**

  1. **Galaxies & Cosmology** This theme includes a sizable fraction of projects that are detection experiments. Therefore the requirements for absolute calibration are relatively low for this theme as a whole. No clear picture emerges about the requirements for repeatability. The requirements on relative calibration are high and driven by the need to obtain accurate spectral slopes and line ratios.
  2. **Star and Planet Formation** The requirements for absolute calibration for this theme are somewhat higher than for theme 1, owing to the larger fraction of projects that aim to determine masses or column densities. Requirements for repeatability are also higher, because many projects combine data from different array configurations or carry out mosaics. The requirements for relative calibration are driven by the need to obtain accurate spectral slopes and line ratios.

3. **Stars and Their Evolution** Requirements for absolute calibration are similar as for theme 2. Variability is a common science target here, and the requirements for repeatability are high. The motivation for high relative calibration accuracy are the same as for theme 2.
4. **Solar System** Some Solar System observations allow internal calibration, relaxing the need for accurate absolute calibration, while other projects seek to determine properties of the surface of the studied objects, requiring high accuracy for the absolute calibration. Good repeatability is important to trace variability and time evolution. Again, the need for accurate spectral slopes and line ratios leads to high requirements on the relative calibration.

- **Other Aspects**
  - Astrometric measurements require good, absolute *phase* calibration.
  - To use line shapes to infer velocity fields requires good, absolute *frequency* calibration.

2.2 Calibration Requirements

The distribution of calibration requirements as listed in Appendix B and plotted in Appendix C show no clear differences between bands and between science topics. In general the following picture emerges:

Absolute Calibration The majority of projects (70–80%) can be successfully carried out with an absolute calibration accuracy $\geq 5\%$, but several applications require 1–3%.

Repeatability About one-third of the projects require a repeatability as high as 1–3%. The other two-thirds are approximately equally split between 5% and 10%.

Relative Calibration (both within one and between different bands) Most projects have requirements equally split between 1–3% and 5%.

Polarization Calibration Too few projects in the DRSP use polarization measurements to draw any conclusions on the required accuracy. The few that do, require accuracies of a few %, or 10° on the angle and 1% on the amplitude.

A Questionnaire on Required Calibration Accuracy

Name author:

DRSP number(s):

DRSP name(s):

1. What is the required absolute calibration accuracy to reach your science goals?

   1-3%, 5% or 10%?

   Please give short motivation:

2. What is the required repeatibility of the flux of your line or continuum to reach your science goals? The timescale between observations can range from a few days to months or even a year. Please consider also the archival value of your data.

   1-3%, 5% or 10%?

   Please give short motivation:

3. What is the required relative calibration accuracy to reach your science goals? Here 'relative' can apply to lines or continuum, either within one receiver band or between different receiver bands (e.g., line ratios, SED slope).

   Within one receiver band: 1-3%, 5%, or 10%?

   Between receiver bands: 1-3%, 5% or 10%?

   Please give short motivation:

4. Requirement on polarization calibration accuracy (if applicable):

5. Any other comments:

B Results Tables

(See next pages)

Table 1: **Calibration Requirements ALMA Design Reference Science Plan**

Obs Mode[a]	Absolute Calibration					Repeatability					Relative Calibration in Band					Relative Calibration between Bands				
	NoRq[b]	1%	1–3%	5%	10%	NoRq	1%	1–3%	5%	10%	NoRq	1%	1–3%	5%	10%	NoRq	1%	1–3%	5%	10%
Number of projects with indicated accuracy requirements																				
band 3 line	0	0	2	9	11	1	0	8	4	9	4	1	7	9	1	1	0	10	10	1
band 6 line	0	0	1	16	26	5	0	12	13	13	5	1	4	24	9	7	0	9	18	9
band 7 line	0	0	0	11	19	5	0	9	10	6	6	0	5	15	4	0	0	11	15	4
band 9 line	0	0	0	1	4	2	0	1	2	0	0	0	1	4	0	0	0	1	4	0
all bands line	0	0	3	37	60	13	0	30	29	28	15	2	17	52	14	8	0	31	47	14
band 3 cont	0	0	3	7	6	0	0	5	5	6	9	0	4	2	1	1	0	7	7	1
band 6 cont	0	0	2	8	6	0	0	5	5	6	10	0	4	2	0	0	0	8	8	0
band 7 cont	1	0	5	4	6	1	0	6	3	6	6	0	6	2	2	2	0	7	5	2
band 9 cont	0	0	1	2	2	0	0	3	1	1	2	0	2	1	0	0	0	4	1	0
all bands cont	1	0	11	21	20	1	0	19	14	19	27	0	16	7	3	3	0	26	21	3
band 3 l+c	0	0	5	16	17	1	0	13	9	15	13	1	11	11	2	2	0	17	17	2
band 6 l+c	0	0	3	24	32	5	0	17	18	19	15	1	8	26	9	7	0	17	26	9
band 7 l+c	1	0	5	15	25	6	0	15	13	12	12	0	11	17	6	2	0	18	20	6
band 9 l+c	0	0	1	3	6	2	0	4	3	1	2	0	3	5	0	0	0	5	5	0
all bands l+c	1	0	14	58	80	14	0	49	43	47	42	2	33	59	17	11	0	57	68	17
Percentage of projects with indicated accuracy requirements																				
band 3 line	0	0	9	41	50	5	0	36	18	41	18	5	32	41	5	5	0	45	45	5
band 6 line	0	0	2	37	60	12	0	28	30	30	12	2	9	56	21	16	0	21	42	21
band 7 line	0	0	0	37	63	17	0	30	33	20	20	0	17	50	13	0	0	37	50	13
band 9 line	0	0	0	20	80	40	0	20	40	0	0	0	20	80	0	0	0	20	80	0
all bands line	0	0	3	37	60	13	0	30	29	28	15	2	17	52	14	8	0	31	47	14
band 3 cont	0	0	19	44	38	0	0	31	31	38	56	0	25	13	6	6	0	44	44	6
band 6 cont	0	0	13	50	38	0	0	31	31	38	63	0	25	13	0	0	0	50	50	0
band 7 cont	6	0	31	25	38	6	0	38	19	38	38	0	38	13	13	13	0	44	31	13
band 9 cont	0	0	20	40	40	0	0	60	20	20	40	0	40	20	0	0	0	80	20	0
all bands cont	2	0	21	40	38	2	0	36	26	36	51	0	30	13	6	6	0	49	40	6
band 3 l+c	0	0	13	42	45	3	0	34	24	39	34	3	29	29	5	5	0	45	45	5
band 6 l+c	0	0	5	41	54	8	0	29	31	32	25	2	14	44	15	12	0	29	44	15
band 7 l+c	2	0	11	33	54	13	0	33	28	26	26	0	24	37	13	4	0	39	43	13
band 9 l+c	0	0	10	30	60	20	0	40	30	10	20	0	30	50	0	0	0	50	50	0
all bands l+c	1	0	9	38	52	9	0	32	28	31	27	1	22	39	11	7	0	37	44	11

[a] Available as a spreadsheet at `http://www.strw.leidenuniv.nl/~alma/drsp_calib_stats1.xls`

[b] NoRq = Projects with no requirements for accuracy

Table 2: **Calibration Requirements per Science Category**

[a]	Absolute Calibration					Repeatability					Relative Calibration in Band					Relative Calibration between Bands				
	NoRq[b]	1%	1–3%	5%	10%	NoRq	1%	1–3%	5%	10%	NoRq	1%	1–3%	5%	10%	NoRq	1%	1–3%	5%	10%
Number of projects with indicated accuracy requirements																				
Theme 1[c]	0	0	1	12	17	0	0	8	6	16	13	0	4	12	1	4	0	11	14	1
Theme 2[d]	0	0	0	11	7	0	0	8	9	1	5	1	3	9	0	4	0	9	5	0
Theme 3[e]	0	0	0	7	4	0	0	4	2	5	3	0	4	2	2	1	0	3	5	2
Theme 4[f]	1	0	7	1	17	6	0	7	4	9	1	0	7	9	9	1	0	7	9	9
Percentage of projects with indicated accuracy requirements																				
Theme 1	0	0	3	40	57	0	0	27	20	53	43	0	13	40	3	13	0	37	47	3
Theme 2	0	0	0	61	39	0	0	44	50	6	28	6	17	50	0	22	0	50	28	0
Theme 3	0	0	0	64	36	0	0	36	18	45	27	0	36	18	18	9	0	27	45	18
Theme 4	4	0	27	4	65	23	0	27	15	35	4	0	27	35	35	4	0	27	35	35

[a] Available as a spreadsheet at `http://www.strw.leidenuniv.nl/~alma/drsp_calib_stats2.xls`
[b] NoRq = Projects with no requirements for accuracy
[c] Galaxies & Cosmology
[d] Star and Planet Formation
[e] Stars and their Evolution
[f] Solar System

C Plotted Results

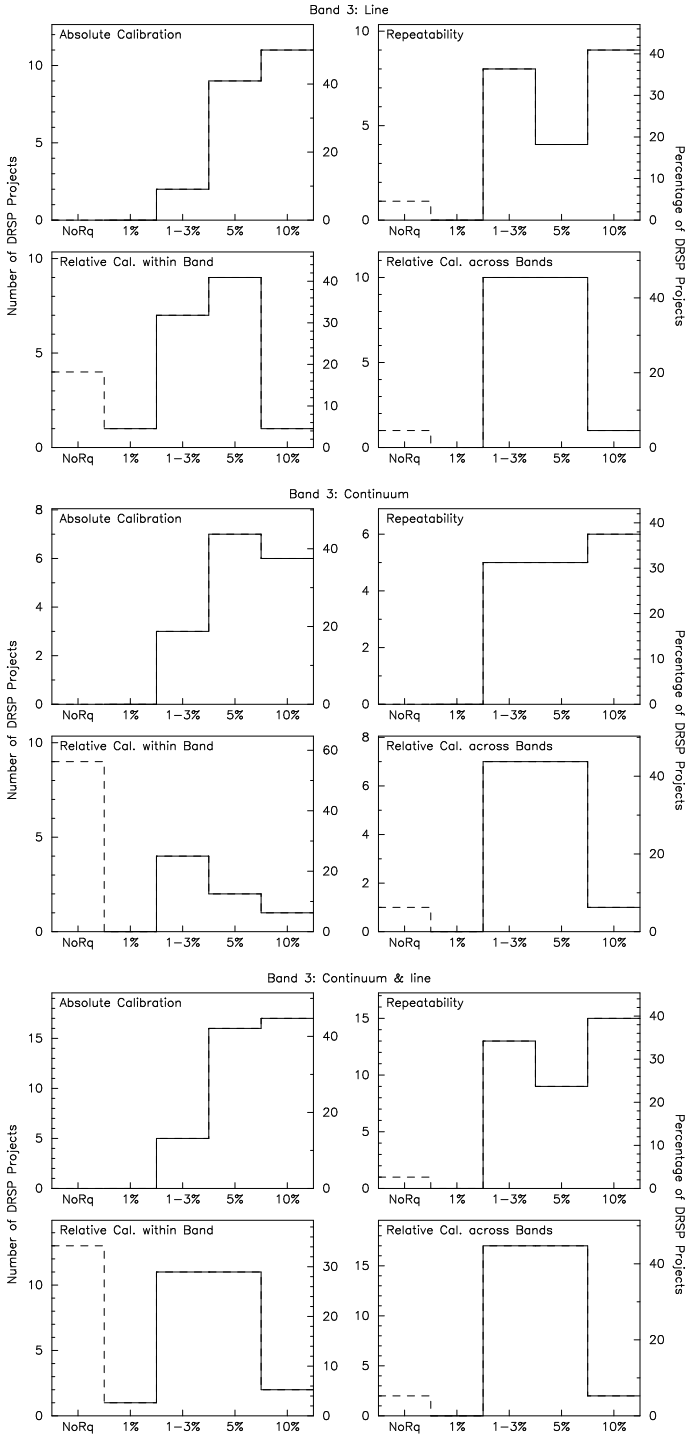

Figure 1: Calibration requirements for Band 3. NoRq = Projects without specific requirements. The y-axis on the right-hand side of each panel is labeled in absolute number of projects, and on the left-hand side in percentage of projects.

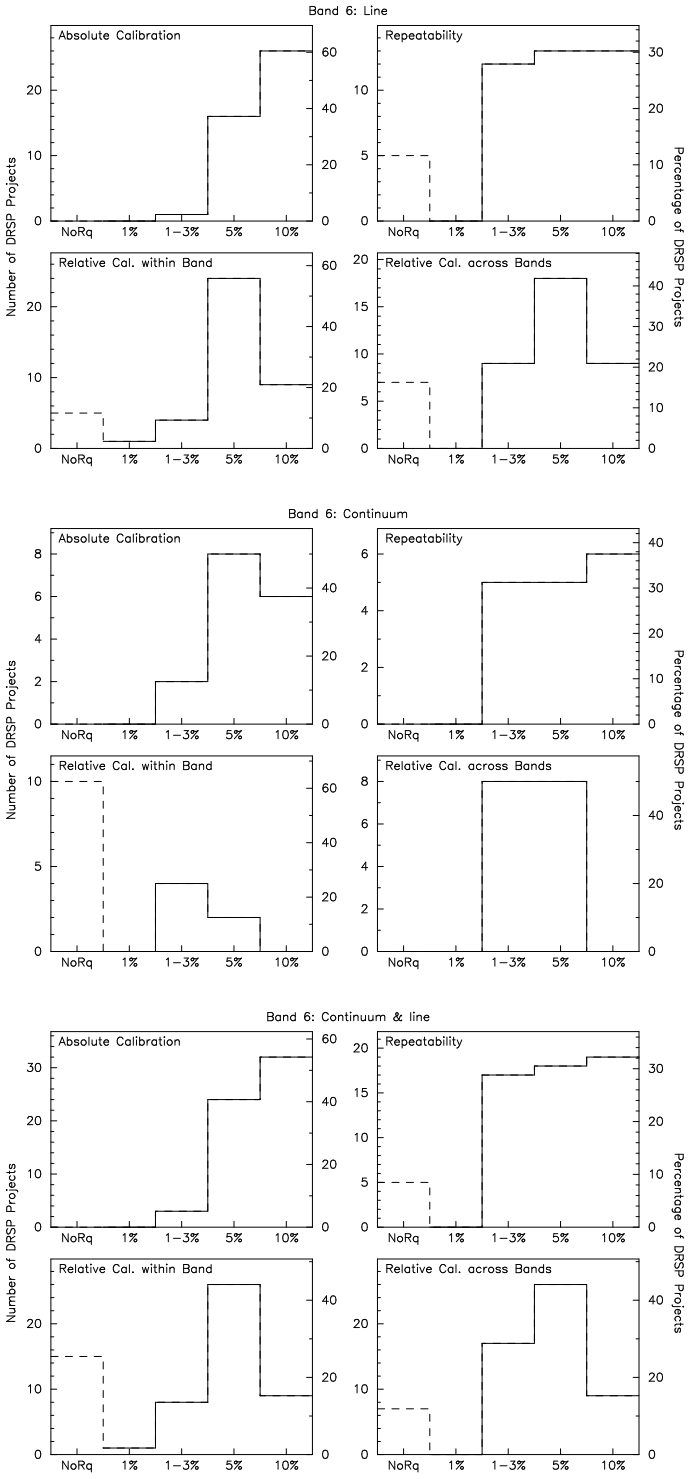

Figure 2: Calibration requirements for Band 6

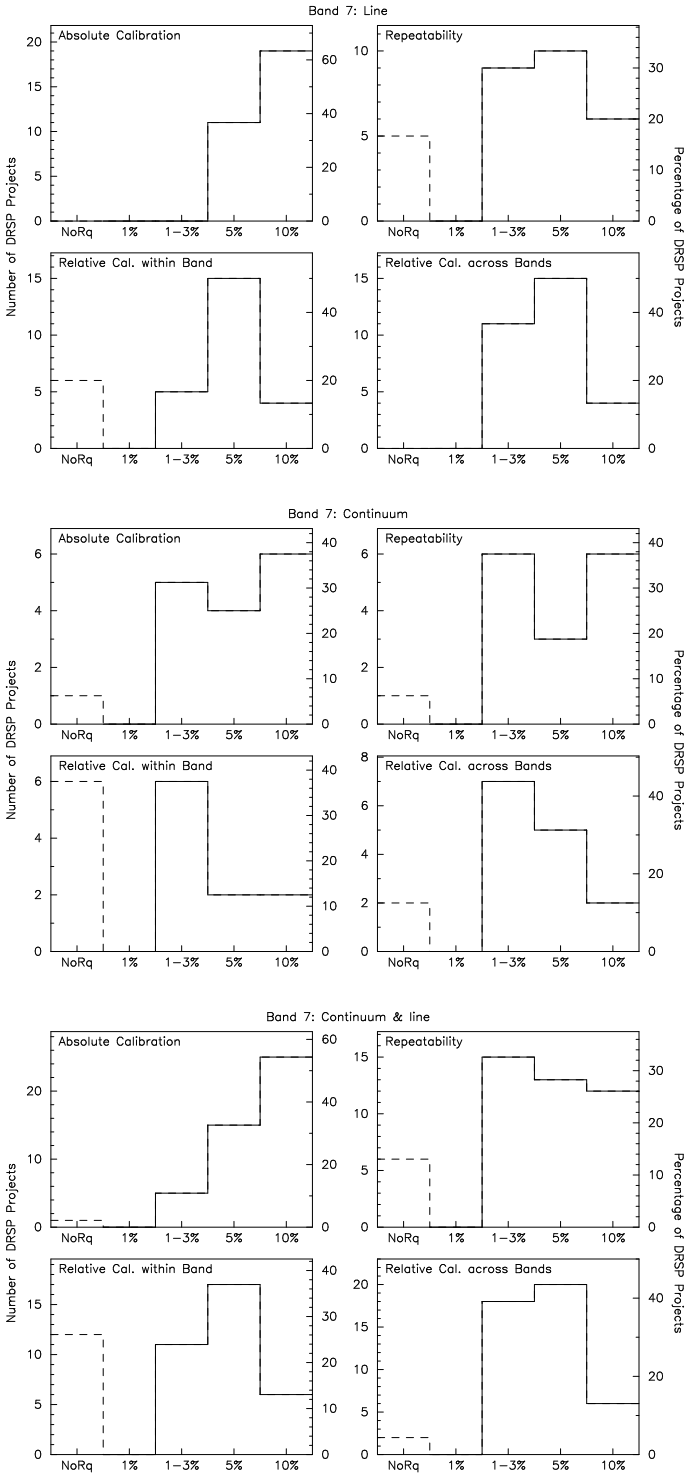

Figure 3: Calibration requirements for Band 7

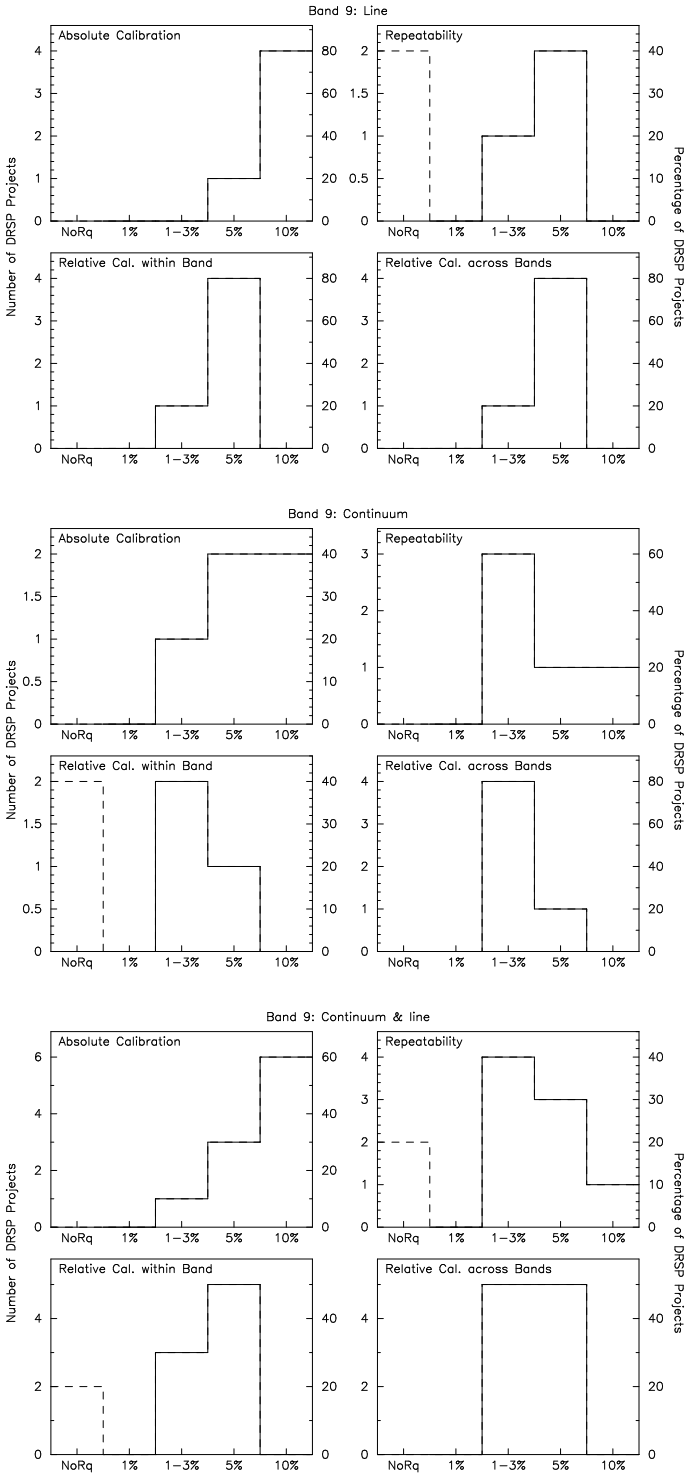

Figure 4: Calibration requirements for Band 9

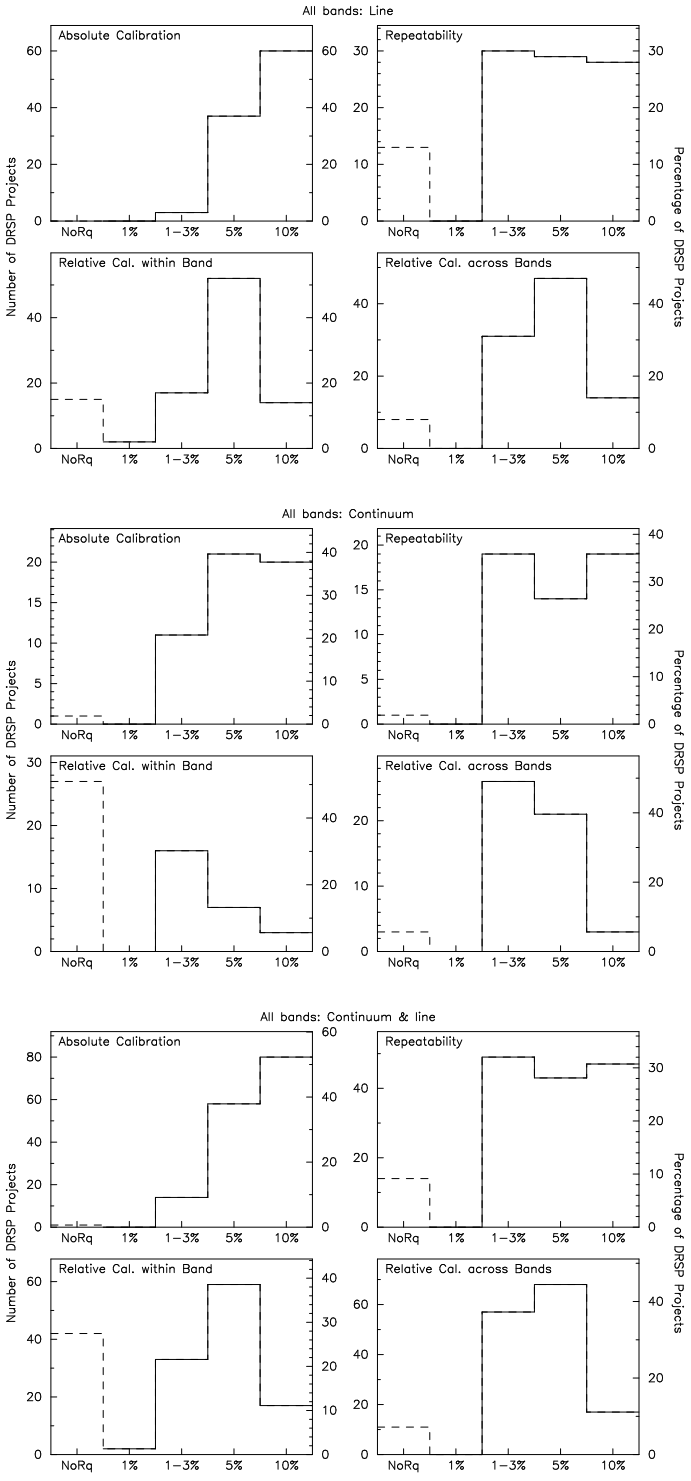

Figure 5: Calibration requirements for all bands

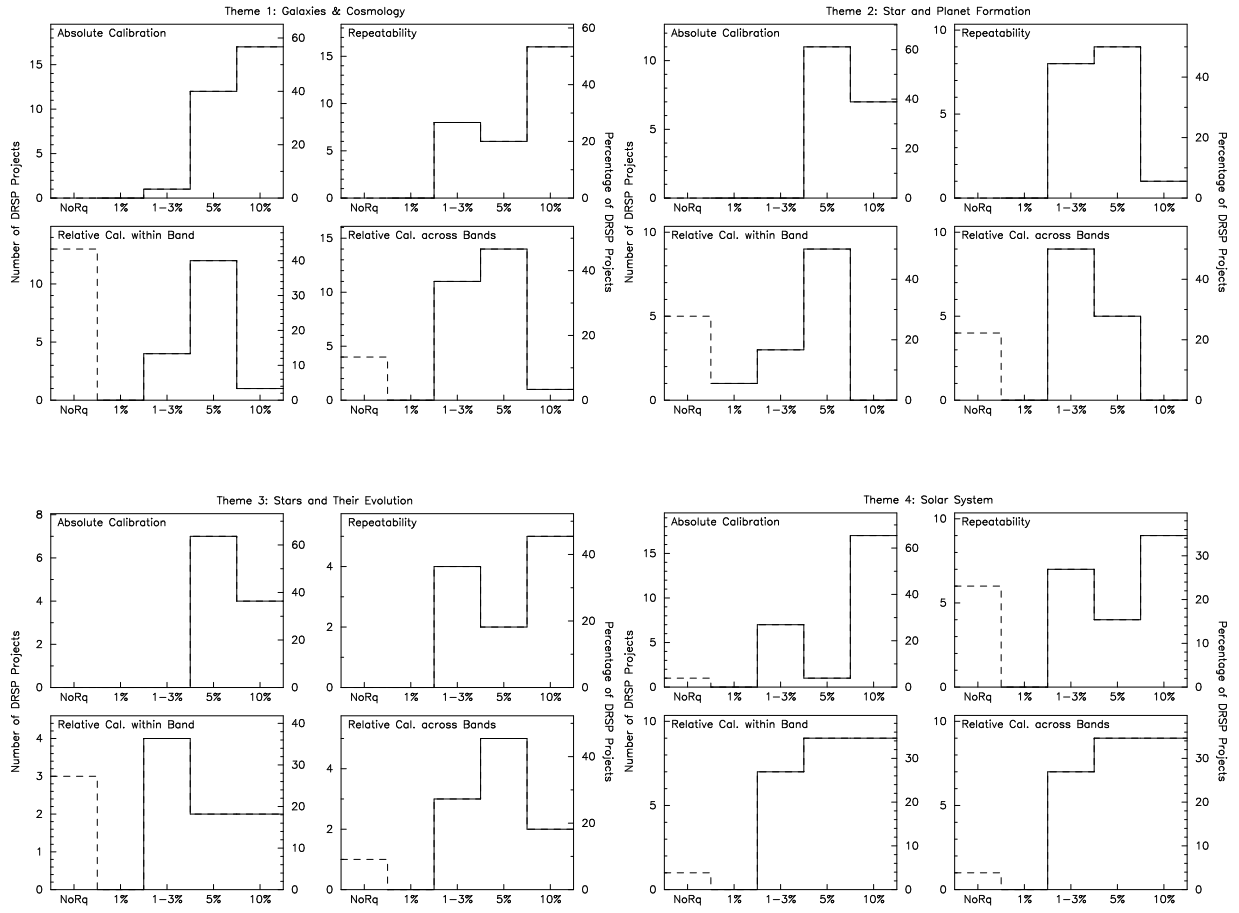

Figure 6: Calibration requirements for the four science categories.