PRODUCTION
TUNABLE FILTER BANK CARD

TECHNICAL SPECIFICATION

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Change Record

Revision	Date	Affected Paragraphs(s)	Reason/Initiation/Remarks
A	2006-01-04	All	First issue. The production TFB card specification is much similar to that of the prototype TFB card.
	2006-01-26		Minor additions in various sections.
	2006-02-03		Additions in Sections on Reliability (TFB low power mode) and Marking.
	2006-02-8	Section 5.3 on Filter	Changes made to reflect 4 spectral point overlap in 2 adjacent subchannels.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF REQUIREMENTS

1 PURPOSE OF THE DOCUMENT

This document describes the main technical specifications of the production Tunable Filter Bank (TFB) card. The TFB cards are part of the ALMA Correlator Station racks which are located in the correlator room of the AOS technical building.
The prototype TFB card specifications are given in [RD 05]. Because the functions of the digital filter card have not changed since the prototype card design, the production TFB card specifications are similar or close to those in [RD 05].

2 RELATED DOCUMENTS AND DRAWINGS

2.1 Applicable Documents List (ADL)

No.	Document Title	Date	Reference
AD 01	ALMA Product Assurance Requirements		ALMA-80.11.00.00-001-B-GEN
AD 02	64 Antenna Correlator Specifications and Requirements	2005-05-10	ALMA-60.00.00.00-001-B-SPE
AD 03	ICD Between: AOS Technical Building And: Baseline Correlator	2005-10-26	ALMA-20.01.02.00-60.00.00.00-A-ICD
AD 04	ICD From: Back End To: Correlator	2004-11-17	ALMA-50.00.00.00-60.00.00.00-A-ICD
AD 05	ICD From: Correlator To: Correlator Computing Software	2005-04-08	ALMA-60.00.00.00-70.40.00.00-A-ICD
AD 06	Tunable Filter Bank Card, Functional Description	2005-04-07	CORL-60.01.07.00-001-B-SPE
AD 07	Internal ICD, From : Tunable Filter Bank Card To : Baseline Correlator Station Motherboard	2005-04-20	CORL-60.01.07.00-60.01.01.00-A-ICD
AD 08	Embedded Software Standards	2004-09-07	ALMA-70.20.00.00-008-A-STD
AD 09	ALMA System Electrical Design Requirements	2004-08-10	ALMA-80.05.00.00-005-C-SPE
AD 10	ALMA System Electromagnetic Compatibility Requirements	2004-08-10	ALMA-80.05.01.00-001-B-SPE

Table 1. Applicable Documents List

2.2 Reference Documents List (RDL)

No.	Document Title	Date	Reference
RD 01	Enhancing the Baseline ALMA Correlator Performances with the Second Generation Correlator Digital Filter System	2003-08-27	ALMA Memo 476
RD 02	Correlator Control Bus Manual		CORL-60.00.00.00-020-A-MAN
RD 03	Programming Manual for Tunable Filter Bank	2005-12-13	CORL-60.01.07.00-002-E-MAN
RD 04	Data processing in the ALMA Tunable Filter Bank	2005-08-11	CORL-60.01.07.00-013-A-MEM
RD 05	Prototype Tunable Filter Bank Card, Technical Specification	2005-04-11	CORL-60.01.07.01-010-A-SPE
RD 06	ALMA Documentation Standards	2003-12-02	ALMA-80.02.00.00-003-F-STD
RD 07	Sub-channel stitching and truncation errors in the ALMA Tunable Filter Bank		CORL-60.01.07.012-A-DOC
RD 08	Tunable Filter Bank Software Meeting Notes	2004-10-29	Correlator TFB meeting notes, A.Baudry
RD 09	Tunable Filter Bank FIR Chip, VHDL Description	2006-02	CORL-60.01.07.03-001-C-GEN
RD 10	Test Manual for TFB	2006-02-03	CORL-60.01.07.00-004-C-MAN

Table 2. Reference Documents List

2.3 Abbreviations and Acronyms

A list of used acronyms is given below.

ALMA   Atacama Large Millimeter Array
AOS   Array Operation Site
CPLD   Complex Programmable Logic Device
CVS   Concurrent Version System (firmware configuration management)
DTS   Data Transmission Subsystem
ESD   Electro Static Discharge
ESO   European southern Observatory
FPGA   Field Programmable Gate Array
IPT   Integrated Project Team
LO   Local Oscillator
NRAO   National Radio Astronomy Observatory
OSF   Operations Support Facility
TFB   Tunable Filter Bank

2.4 Verb Convention

"Shall" is used whenever a specification expresses a provision that is binding. The verbs "should" and "may" express non-mandatory provisions.

"Will" is used to express a declaration of purpose on the part of the design activity

2.5 Requirements numbering

The requirements within the present document are numbered according to [RD 06], with the following code:

[CORL-60.01.07.05-XXXX-YY / Z(ZZ)]

Where:

CORL-60.01.07.05 identifies the correlator TFB production board;

XXXX is a consecutive number 0010, 0020, (the nine intermediate numbers remaining available for future revisions of this document);

YY describes the requirement revision. It starts with 00 and is incremented by one with every requirement revision;

Z(ZZ) describes the requirement verification method(s). Where T stands for Test, I for Inspection, R for Review of design and A for Analysis.

3 GENERAL DESCRIPTION

The Tunable Filter Bank (TFB) is made of 32 independently tunable digital filters. Each filter is completely independent and drives one input of the station card. The TFB processes the signal provided from one digital sampler in one given sense of polarization to transform each 2 GHz IF channel input into 32 sub-channels. In addition, the filter bank allows the correlator to process the signal either in the time division mode or in the frequency division mode, each correlator plane processing respectively one segment in time or in frequency. This system is described in detail in [RD 01] and [AD 02].

Each filter being independently tunable, the correlator resources can be used for mixed spectral modes with zoom windows on specific spectral features within the IF bandwidth.

Each Tunable Filter Bank (TFB) card includes 32 digital filters (implemented in 16 large Field Programmable Gate Arrays, FPGAs) and there are 8 such cards per antenna to process all four IF baseband pairs for two different senses of polarization.

	PRODUCTION	Doc: CORL-60.01.07.05-004-A-SPE
ALMA		Date: 2006-03-17
	TUNABLE FILTER BANK CARD	Status: Approved
		Page: 9 of 17
	Technical Specification	
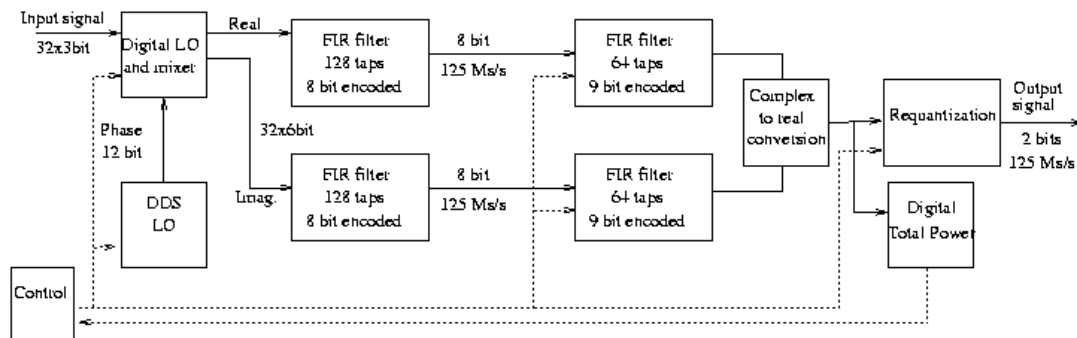
Figure 1. **Digital filter block diagram**

Each one of the 32 digital filters in each TFB card has the structure described in Figure 1. The input signal, sampled at 4 GS/s, 3 bits per sample, is processed by the filter as follows:

- The input signal is converted using a mixer/local oscillator operating in the complex domain. The band of interest, 62.5 MHz, is converted into the frequency range ±31.25 MHz.

- The desired bandwidth is filtered using a two stage, decimating filter.

- The resulting complex signal is up-converted by 31.25 MHz in order to obtain a real signal sampled at 125 MS/s.

- The real signal is re-quantized to 2 bits to be consistent with the nominal 2-bit correlator mode. (4-bit re-quantization and 4-bit mode is also available.)

The main functions of the TFB card are described in [AD 02] and [AD 06]. They are implemented in large FPGAs and the most recent FPGA technology is used in the production cards. Each TFB card contains also smaller FPGAs to implement the fine delay as briefly described in Section 5.1. These devices behave as input signal buffers to the digital filter sub-system shown in Figure 1. In addition, there are 2 small CPLDs on each board; one is an interface chip used to download the FPGA personalities and to allow the system to monitor the TFB processing in the FPGAs (filter shapes and bandwidths control), and the other one is used for FPGA software error monitoring.

4   TOP LEVEL SPECIFICATIONS

4.1   General requirements

[CORL-60.01.07.05-0010-00/T] Power, Thermal and Mechanical specs as per [AD 03], [AD 07]

The filter card will be operated in the Correlator Station rack of the ALMA Correlator room in the AOS technical building. The power, thermal and mechanical constraints and general operation conditions of the correlator subsystem are given in [AD 03] and [AD 07].

4.1.1   Technology

[CORL-60.01.07.05-0020-00/R] Mature Technology

The TFB shall use mature technology whenever possible.

4.1.2 Design Standards

[CORL-60.01.07.05-0030-00/R] Design Standards according to [AD 09], [AD 10]

The design shall be carried out meeting the requirements and the recommendations contained in [AD 09], [AD 10].

4.1.3 Series production

[CORL-60.01.07.05-0040-00/R] Design suitable for Series Production

The TFB shall give a high degree of consideration to reduction of production and assembly costs. Complexity of the design and mechanical structures should be simplified wherever possible.

4.1.4 Standard parts

[CORL-60.01.07.05-0050-00/R] Standard Parts shall be used where possible

Standard, unmodified commercially available components shall be used where possible.

4.1.5 Mechanical tuning

[CORL-60.01.07.05-0060-00/R] No mechanical tuning needed

No mechanical tuning shall be needed during operation of the TFB.

4.1.6 Metric hardware

[CORL-60.01.07.05-0070-00/R] Metric hardware shall be used

All hardware used in the TFB, including but not limited to fasteners, tapped holes, etc., shall be metric whenever possible.

4.2 Mechanical/electrical interface

[CORL-60.01.07.05-0080-00/T] Plug-in compatibility with original filter

The TFB shall be a plug-in replacement of the original correlator filter board, as specified in [AD 07].

Each filter card interfaces with the DTS receiver card on one side, receiving the output of one sampler, and provides 32 outputs to the correlator station board.

[CORL-60.01.07.05-0090-00/T] Supply Voltage compliant with [AD 07]
[CORL-60.01.07.05-0100-00/T] Current not to exceed requirements in [AD 07]
[CORL-60.01.07.05-0110-00/T] Power Dissipation not to exceed 130 W as per [AD 07]

4.2.1 Input data

[CORL-60.01.07.05-0120-00/T] Input data: 32 3-bit consecutive samples @125 MHz

The input data stream shall be organized as 32 3-bit consecutive samples, clocked at 125 MHz. Sample encoding is recovered from the decoders in the DTS card; it is Gray code as defined by the sampler ASIC design and recalled in [AD 07].

4.2.2 Output Data

[CORL-60.01.07.05-0130-00/T] Output data: 32 2-bit samples @125 MHz

The output data stream shall be organized as 32 2-bit samples, clocked at 125 MHz. Each sample represents the output of one independent FIR filter. Two 2-bit signals can be assembled to form a single 4-bit data stream.

4.3 Functionality and mode overview

Each TFB card shall provide two basic functions:

- *Programmable delay steps* in the input data stream (2 GHz bandwidth); one delay step corresponds to 250 ps (4 GSamples/s).

- *Digital filtering of the 2 GHz bandwidth* to obtain 32x2-bit samples clocked at 125 MHz (125 MSamples/s).

There shall be five possible operating modes for the output filter samples. Sample encoding is signed binary, as defined by the correlator ASIC design.

[CORL-60.01.07.05-0140-00/T] Data Encoding Signed Binary

- *Time division mode*
[CORL-60.01.07.05-0150-00/T] Time division mode: multiplex processing

The 2 GHz IF baseband is time multiplex processed (4 GS/s sampling rate). The spectral sub-channels are bypassed and the correlator is operated as a full XF system (X-lag mode of the baseline correlator) to allow fast dumping rates at low spectral resolution. The filter card simply re-quantizes the input samples from 3-bit to 2-bit code.

- *Frequency division mode*
[CORL-60.01.07.05-0160-00/T] Frequency division mode: 32-62.5MHz tunable 2-bit channels

Each filter card provides 32 independently tunable sub-channels of the input band, each with a bandwidth of 62.5 MHz and 2-bit re-quantization.
The frequency division mode is used to enhance the spectral resolution, providing, after X-lag correlation and Fourier transform, a hybrid spectrum. The hybrid spectrum is reconstructed by stitching together, with some overlap, all of the individual sub-channel spectra.

Adjacent filters (sub-channels) can be combined to provide other options:

- 4-bit mode
[CORL-60.01.07.05-0170-00/T] Four bits mode: 4-bit quantization

4-bit quantization is available by using pairs of digital filters and four correlator planes to derive 4-bitx4-bit products. Various spectral resolutions are possible depending on the correlator configuration (see mode charts in [AD 02]).

- Oversampling mode
[CORL-60.01.07.05-0180-00/T] Oversampling mode: 250MS/s sampling rate

250 MS/s sampling rate is available for different bandwidths to improve the sensitivity (see mode charts in [AD 02]).

- *Half-bandwidth mode*
[CORL-60.01.07.05-0190-00/T] Half-bandwidth mode: 31.25 MHz bandwidth, 62.5 MS/s

The smallest total bandwidth can further be reduced to 31.25 MHz with an output data rate of 62.5 MS/s. This mode provides maximum spectral resolution using the oversampling option of the correlator. 4-bit mode is also available in this mode (see mode charts in [AD 02]).

5 FUNCTIONAL REQUIREMENTS

In this Section we give the requirements for individual components of the Tunable Filter Bank card. Some details or brief explanations to justify these requirements are also given. Software requirements are implemented in the filter and delay FPGAs according to the programming manual [RD 03].

5.1 Fine Delay
[CORL-60.01.07.05-0200-00/T] Fine delay: 250ps steps in 0.0-8μs range

This subsystem implements in dedicated FPGAs digital delays with 250 ps steps in the range 0.0 to 8 μs. Delay changes occur at 1ms boundaries and are spread over a time interval of a few tens of nanosecond; the 1ms signal is generated from the Station Control card.

During delay adjustment the samples are invalid; however, no blanking occurs at the correlator or in the TFB card because the resulting glitch is deemed negligible in terms of added noise. The delay range of 8 μs allows us to correct for geometric delay *changes* during a single integration period without modifying the bulk delay setting in the Station card. Changing the bulk delay affects the phase of the digital local oscillator as seen by the correlator; any phase change should be avoided or should be corrected using a phase register. Both possibilities can be implemented in the TFB card (delay changes or phase correction).

5.2 Digital LO/Mixer

The first stage of the TFB card corresponds to the digital/LO and mixer shown in Figure 1.

[CORL-60.01.07.05-0210-00/T] Spurious free dynamic range: 48dB (SNR 0.8%)
[CORL-60.01.07.05-0220-00/T] Digital mixer resolution : 2x6 bit complex

To obtain a spurious free dynamic range of at least 48 dB a 6-bit digital mixer must be implemented.
The corresponding SNR degradation is 0.8 % and the mixer thus converts the input signal stream from 3-bit real to 2x6-bit complex.
Any spurious product is proportional to the input signal; hence, the 48 dB spurious free specification corresponds to the maximum spectral signal (e.g. RFI or harmonic levels) which can be tolerated in the input IF baseband.

[CORL-60.01.07.05-0230-00/T] LO resolution: 30.5kHz

The frequency resolution of the LO is 30.5 kHz (12-bit DDS accumulator at 125 MHz equivalent to $4 \text{ GHz}/2^{17}$) and the frequency range is 0-2 GHz. (This resolution corresponds to 1/1024 of the minimum available bandwidth.)

[CORL-60.01.07.05-0240-00/T] Frequency change effective at 1ms boundary

The required frequency is loaded in a specific register in synchronism with 1ms pulses. The phase is always cleared when the frequency is changed in order to have exactly the same phase for any mixer throughout the correlator system.

[CORL-60.01.07.05-0250-00/T] Programmable Phase Offset

A programmable phase offset must be added to the digital LO because the bulk delay is inserted in the Station card after the TFB frequency conversion. Each time the delay changes the phase as seen by the correlator also changes and one must compensate for this effect. The net LO phase at time t is thus $\phi(t) = \phi_0 + f(t-t_0)$, with ϕ_0 = phase offset, f = programmed frequency, and t_0 = 1ms boundary at which the frequency is updated.
The frequency and phase updates must be fully synchronized for all 32 filters; details of this operation are given in [RD 03].

5.3   Filter

There are two filter stages following the digital LO/Mixer (Figure 1); the first one is a fixed tap, decimation filter, and the second one has loadable taps. The filter shape is primarily given by the second stage while the first stage drives the overall filter rejection.

The nominal 62.5 MHz filter performances (with preloaded tap coefficients) are given below. The effective bandwidth with respect to the nominal bandwidth depends on the number of overlapping spectral points when all subchannels are stitched together; this number can be selected by the users. The passband is chosen in order to obtain a continuous, high quality spectrum with an overlap of 4 adjacent spectral points ('standard' overlap) out of 64.

[CORL-60.01.07.05-0260-00/T]	Minimum stopband reject. (1st & 2nd stages)	47 & 45 dB
[CORL-60.01.07.05-0270-00/T]	Average stopband rejection (1st stage)	> 50 dB
[CORL-60.01.07.05-0280-00/T]	Passband ripple	0.3 dB p-p
[CORL-60.01.07.05-0290-00/T]	Passband (w.r.t. nominal)	3.125-96.875%
[CORL-60.01.07.05-0300-00/T]	Passband (MHz)	1.95-60.55 MHz
[CORL-60.01.07.05-0310-00/T]	Useful bandwidth	93.75%

In the above passband, the 4 overlapping spectral points are shared between 2 adjacent subchannels (2 in subchannel N and 2 in sub channel N+1) and the effective bandwidth is thus 60/64 = 93.75% or 58.6 MHz. The passband is 3.125% (2/64) to 96.875% (62/64) with respect to nominal or 1.95 to 60.55 MHz.

When the correlator is used in the frequency division mode with all digital filters active the effective bandwidth is not the original 2GHz but, in the case of 4 overlapping spectral points, 93.75% x 2 GHz = 1.875 GHz. Therfore, 62.5 MHz (125 MHz/2) are wasted on each side of one 2 GHz IF channel. .

In the half-bandwidth mode, 31.25 MHz, the following parameters are affected (with twice more overlapping spectral channels):

- Passband (w.r.t. nominal)	6.25-93.75%
- Passband (MHz)	1.95-29.30 MHz
- Useful bandwidth	87.5%

In the latter mode it is not meaningful to stitch together independent sub-channels. This mode is used only to increase the spectral resolution when all the available correlation resources are used to analyze one single sub-channel. A maximum spectral resolution of 3.8 kHz (31.25 MHz/8192) is then achievable in one single sense of polarization; this is well above the science maximum spectral resolution requirement.

5.4   Output stage

The last stage of the digital filter offers various quantization and oversampling modes after the two filtered data streams (real and imaginary) have been converted to real data. Specifications are listed in Section 4.3 of this document and recalled below:

- *Time division mode:* the filter section is bypassed and the input 3-bit data is re-quantized to 2 bits. The total SNR degradation is that due to the 2-bit quantization, i.e. around 12%. Less degradation is available when one polarization only is being processed. In that case, because there is one single baseband signal to drive 2 filter cards the correlator performs a 3-bit correlation; see mode charts in [AD 02].
- *2-bit mode:* this is the normal mode of operation. 2-bit quantization introduces a SNR degradation of 12% in addition to that due to the 3-bit sampler (3.7%) and to some mixer degradation.
- *4-bit mode:* in this mode one uses two sub-channels in parallel and 4 correlator planes to reduce the SNR losses to 1.2% in the final quantization stage.
- *Oversampling mode:* in this mode one uses two sub-channels and two correlator planes in parallel to reduce the SNR losses by 6% in the final quantization stage. 4-bit twice Nyquist is also available (see mode charts in [AD 02]).

The total power level is measured for each of the 32 sub-channels to dynamically adjust the quantization thresholds in the different modes (see [RD 03]).

6   REQUIREMENTS ON SIGNAL POST-PROCESSING

When the correlator is operated in the frequency division mode, the spectral quality of the reconstructed spectrum depends on the sub-channel alignment and calibration procedure. Although not strictly part of the TFB Technical Specification we recall below some requirements concerning signal processing. These questions are addressed in e.g. [RD 07] and [RD 08].
Because each sub-channel is individually re-quantized before it is cross-correlated, different sub-channels across a selected bandwidth must be stitched together and a differential/absolute calibration goal must be specified in order to achieve good platforming performances. Differential calibration requires some form of total power monitoring, e.g. by measuring zero-lag correlation, and correcting for 2-bit quantization with a level dependent correction function. A relative calibration error between sub-channels better than 0.1% should be achievable.

The correlator zero-lag measurement does not require any special soft- or hardware requirement for the TFB card design.

7   FIRMWARE STANDARDS

This section applies to both the firmware developed for the FPGA's (see [RD 09]) and the software developed for the test equipment or Test Fixture required to assess the TFB card performances (see [RD 10]).

[CORL-60.01.07.05-0320-00/R] Firmware Standards: according to [AD 08] where possible

The firmware developed for the TFB shall be in accordance to [AD 08]. Specifically:

[CORL-60.01.07.05-0330-00/R] Development environment: under Microsoft Windows OS
[CORL-60.01.07.05-0340-00/R] Firmware Configuration. Management: CVS or similar

A firmware Configuration Management shall be implemented by Concurrent Version System (CVS) or similar/equivalent system.

The documentation produced and archived with each firmware release includes the TFB VHDL source files and the TFB programming files together with other useful files (e.g. tap weights tables). Releases are made according to firmware standards [AD 08] mentioned above.
The documentation shall include a README file listing the release files, their content and their relationship and a RELEASE NOTES file describing the main features of the release.
[CORL-60.01.07.05-0350-00/R] Documentation: README and RELEASE NOTES

8 ENVIRONMENTAL SPECIFICATIONS

Temperature

[CORL-60.01.07.05-0360-00/A] Operating Temperature: **+10 to +30 °C**
[CORL-60.01.07.05-0370-00/A] Storage Temperature: **-30 to 70 °C**
[CORL-60.01.07.05-0380-00/A] Minimum Air Pressure: **490 mbar**

Relative Humidity

[CORL-60.01.07.05-0390-00/A] Relative Humidity Operating , storage: **0-95%**

9 ELECTRO-MAGNETIC COMPATIBILITY

[CORL-60.01.07.05-0400-00/A] Electromagnetic Compatibility according to [AD 10]

Implementation of the design shall be such that the requirements stated in [AD 10] are met as closely as possible.

10 SAFETY REQUIREMENTS

Considering the nature of the TFB (low power level, low voltages), no specific safety requirements are envisaged.

11 RELIABILITY AND LIFETIME

The filter card design shall use proven technology so that the overall expected failure rate does not exceed a few events/year.
In the TFB card design a high degree of consideration was given to reduce heat dissipation and thus improve long term reliability. Heat dissipation has been optimized by considering the performances of the latest FPGA firmware tools. In addition, for the observing modes where all the filter resources are not required (bypass mode for continuum observations or line observations not requiring all 32 sub-channels) the implemented firmware shall switch off the power of all unused filters.

The final reliability analysis shall include the latest power dissipation measurements made with the large FPGAs assembled on the TFB card prototype to derive, in the expected air flow, an estimated number of failures of the design after 20 years operation of all four Correlator quadrants.

12 MAINTENANCE

[CORL-60.01.07.05-0410-00/A] Maintenance-free

The prototype TFB cards are designed for maintenance-free operation.
As for the prototype cards there is no specific maintenance scheme foreseen.

13 MARKING

[CORL-60.01.07.05-0420-00/I] Marking of each single TFB card unit

Each TFB card shall be marked to identify the device, the unique serial number, the revision.
A Silicon Unique Serial number generator chip shall be implemented to allow the system electronically identify each TFB card.
A cross reference table shall be delivered to relate such number with the Serial number of the TFB.

14 STORAGE AND SHIPMENT

After all TFB cards have undergone visual inspection and electrical and spectral tests for acceptance packing and accompanying documentation shall be provided for delivery to the Correlator integration center.

[CORL-60.01.07.05-0430-00/I] Package suitable for Shipment and Storage

Suitable packing to protect the assembly from shipment hazards (ESD as well as handling) shall be provided for shipment.
The packing shall be suitable for the environmental conditions as specified in section 8.

[CORL-60.01.07.05-0440-00/I] Shipment according to Instructions

The shipment shall conform to the directions for custom clearance given to the contractor prior to delivery.

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