

PROGRAM : SHARAD PHASE E

PLAN

TITLE: SHARAD In-Flight Calibration Plan

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1 Introduction

1.1. Scope

SHARAD on-ground calibration activities have been limited to the characterization of the SEB (SHARAD Electronic Box), not having been possible to perform extensive characterization of the flight antenna nor end-to-end calibrations on ground.

Scope of the present document is to define the activities to be carried out in-flight in order to ensure SHARAD products calibration. This document does not address instrument checkouts (which are covered by RD-01, instead).

The calibration needs are assessed and an overall calibration strategy is then defined, leading to the identification of the data sets to be collected and relevant processing to be applied.

The document also address how to exploit the available calibration data (from both on-ground and in-flight calibration) to correct SHARAD products, and the organization of the calibration database.

1.2. Overview of commissioning activities

The SHARAD commissioning phase, which includes the checkout activity and the in-flight calibrations, spans between the transition phase (before the solar conjunction period, during which contact between MRO and the Earth is lost) and the begin of the primary science phase PSP, after the solar conjunction.

Relevant activities are divided into two phases:

- Checkout : during this phase, SHARAD will perform the deployment of the antenna, followed by a sequence of tests to verify the proper functionality of the instrument. These activities are described in RD-1
- Calibration: the calibration activity is aimed at characterize the antenna pattern, the sensitivity to spacecraft configuration, and to collect "reference" waveforms to be used for signal correlation in the operational phase.

Calibration activities are described within this document.

2. DOCUMENTS

2.1. Applicable Documents

AD-1	MRO-MNDT-001:RFS	MRO Calibration Memo, Issue C
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2.2. Reference Documents

RD-1	PLN-SHE-0009-ALS	SHARAD Commissioning checkout plan
RD-2	PLN-SHE-0005-ALS	PA Plan
RD-3	DC-OSU-006-2005	Allegato Tecnico Gestionale

3. CALIBRATIONS

3.1. Calibrations needs and approach

The calibration data collected during SHARAD on-ground tests cover the behavior of the electronics (SEB) over temperature (characterized on a dummy load simulating the antenna impedance), but do not cover the antenna (whose behavior is, in turn, affected by the spacecraft configuration).

An overall end-to-end characterization is then required to ensure:

- amplitude vs frequency calibration of the passive radiometry data
- radiometric calibration of the radar data, keeping into account that the antenna gain will change as a function of spacecraft configuration (Solar Array and High Gain Antenna position), and that variation over the antenna path shall be characterized (SHARAD may observe also while Spacecraft is pointing off-nadir)

These data shall be combined with the on-ground characterization data (specifically, Tx power and Rx gain vs temperature) to account for temperature variations.

It must be noted that the goal of in flight calibration does not cover **absolute** amplitude calibration (due to the lack of known scatterers on Mars surface), but only relative calibration (pattern and variation with S/C appendages position). Absolute calibration will use on-ground test data from the scaled RF mockup.

Additionally, echo information from flat surface are also exploited to correct the instrument correlation reference function (characterized on-ground at SEB level) in order to include the antenna behavior .

3.1.1. Acquisition classification

To univocally identify an acquisition sequence, an acquisition code will be used for both checkout and calibration acquisitions, according to the following coding scheme:

`<generic type><step#>_<test-id#>-<case-id#>_<class>{<version#>}`

Where:

Generic type: V for checkout and Verification, or C for Calibration

Step#: one digit numerical from 0 to 6 identify calibration step

Test-id#: progressive code of the generic test (2 digits, starting from 01)

Case-id#: progressive of the test case (2 digits, starting from 01)

Class: identifies boundary conditions for the acquisition

Version: identify version if acquisition needs to be repeated (2 digits, starting from 01)

For the calibration acquisition, specifically, "Class" is always "S" (require selected target areas)

Example: C1_02-01_S_01 identifies calibration acquisition #2, subcase #1, first run.

3.2. Passive Radiometric Calibration

Passive radiometric calibration will use data collected during the Rx checkout (see RD-01). No dedicated acquisitions are thus planned for this phase.

3.3. Active Radiometric Calibration

3.3.1. Radiometric Calibration

Radiometric calibration of the radar echoes requires knowledge of:

- transceiver transmitter power and receiver gain
- antenna two-way gain

While the transmitter and receiver characteristics have been deeply characterized on-ground, the antenna gain has to be inferred from the amplitude of radar echo over a surface of known characteristics. The limited knowledge of the target area sigma-0 may prevent any accurate absolute calibration, but has no effect on the relative calibrations, which is divided into:

- pattern characterization, performed by measuring the nadir echo at different spacecraft attitudes
- characterization vs spacecraft configuration, performed by measuring the nadir echo with different positions of solar array and HGA.

One major assumption is done in developing the calibration approach: that the antenna radiation beam does not affect significantly the pattern shape in the narrow sector of interest (+/- 10 deg pitch and +/- 30 deg roll) but only its absolute amplitude. This assumption appear both reasonable and necessary, allowing to split the characterization into two independent measurements (gain at a fixed – nadir – direction vs S/C configuration, and pattern at ‘nominal’ S/C configuration) while, otherwise, a complete pattern characterization would have been required for each S/C configuration, entailing an extremely long (so long as to be practically unfeasible) calibration phase.

The definition of S/C configuration to be applied in the different calibration steps is addressed in para 3.3.2.

Note about conventions: the S/C axes wrt the direction of flight are reported in fig 3.3-1

We will use here the term “pitch” to indicate a rotation around the “Y” axis and “roll” to indicate rotation around X axis. SHARAD antenna is parallel to the “X” axis.

Radiometric calibration will then be performed in the following steps:

Nominal Reference Conditions

These acquisitions serve both as reference for the radiometric calibration, and for the calibration of the reference function.

While, in principle, only one acquisition is required, an adequate number of them allows to average the results with consequent improved accuracy. The number of acquisitions is then defined in 6 (TBC).

Acquisition Definition for nominal reference acquisition

The following regions could be used as targets:

Flat areas – northern polar region preferred

Test Code: C1_01-xx_S (xx from 01 to 06)

Class: S

S/C attitude: Nadir pointing

SS mode, Atten = 10 dB (TBC), 8 bit, no presuming , open loop

Acquisition duration: 20 sec

Perform 6 times.

Pattern Calibration

To perform calibration vs pattern, it is planned to use comparison between repeated tracks (MRO has a repeat period – within few miles of slip between the tracks - of 17 days). These must be selected such to be in a flat and homogeneous area in order to avoid off-nadir returns and to ensure that there is no criticality about acquisition localization. Best candidate are the flatlands in the northern region (above 45°N).

A limit to the maximum latitude may be given by the presence of the CO₂ deposits which, changing in thickness within the repeat period, may led to changes in the reflection coefficient.

This shall not be a problem in the northern hemisphere, considering that the calibration is planned to occur during the northern summer.

The candidate zones for collecting samples are therefore those at latitudes between 45° and 85° N (both ascending and descending), corresponding to about 13 minutes of flight for each zone (note: the planned acquisition duration is 8'10": considering that the edge of the northern flat areas is generally above this latitude – up to 55°N – it would be possible to allocate the required observation, with start/stop latitudes to be defined according to the actual ground track)

The approach is to perform, on the first pass, an acquisition with pitch and roll set to 0 and reference S/C configuration, and an acquisition while the S/C is rolling from -30° to +30° in 6 minutes (10 deg/min roll rate), with -10°, 0° or +10° pitch and S/C in reference configuration.

The data during roll will be sampled every 30 sec (corresponding to 5° roll) with 10 sec acquisitions separated by 20 sec wait mode.

In order to average an adequate number of samples and ensure characterization accuracy, each acquisition pair shall be repeated 3 times.

Acquisition Definition for pattern calibration

Target areas: Flat areas – northern polar region from 45° to 85°N preferred

Test Code: C2_01-xx_S (reference acquisition)

Test Code: C2_02-xx_S (“rolled” acquisition)

(xx from 01 to 03 according to pitch)

Class: S

S/C attitude: pitch -10°, 0°, +10°, rolling from -30° to +30° ascending and from +30° to -30° descending)

SS mode, Atten = 10 dB (TBC), 6 bit (TBC), presuming 4, open loop

Acquisition sequence: 490 sec, alternating 10 sec SS and 20 sec wait. Ends with 10 sec SS (17 x 10 sec SS + 16 x 20 sec WAIT)

Acquisition start must be programmed **60 seconds before** nominal start coordinates and start of roll manoeuvre (ends 60 sec after end of manoeuvre)

Perform 3 x 3 times (N for each value of pitch)

Alcatel Alenia Space Italia S.p.A.

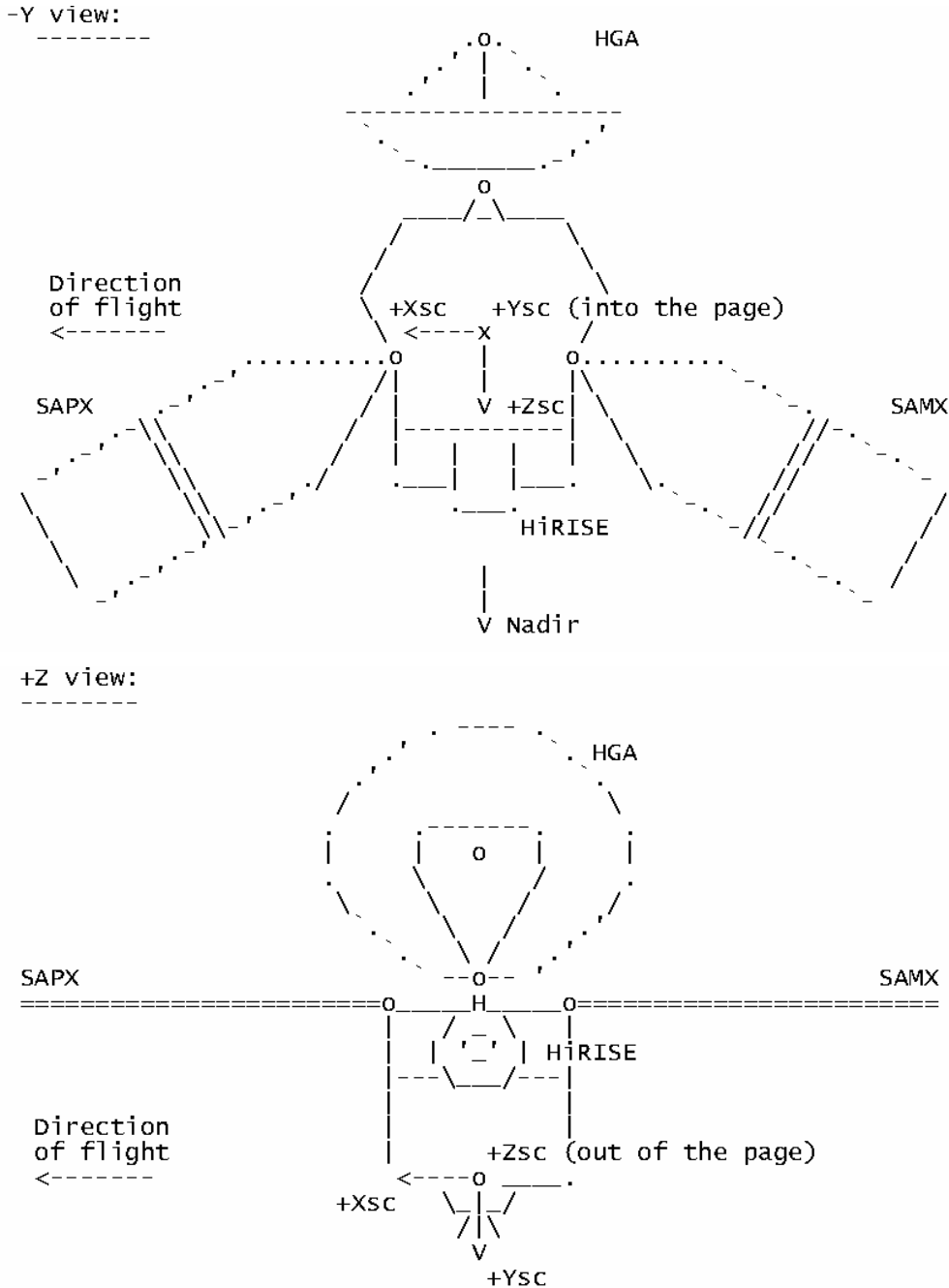


Fig 3.3-1 - MRO reference axes in Mars orbit

Calibration vs S/C configuration

Due to the variation of the antenna gain in dependence of the S/C configuration, a calibration of the antenna gain at nadir is also required for different combination of solar array and HGA position.

Calibration vs solar array and HGA have been decoupled.

Definition of the different configurations is given in 3.3.2

Therefore, the configurations to be calibrated are:

- the 3 SA configurations vs the reference one
- the HGA “out-of-view” configuration vs the “HGA in-view”

To perform this calibration it is possible to exploit cross-overs, performing the first acquisition in the “reference” spacecraft configuration and in one of the other configurations to be characterized.

Several crossovers will be generated at different latitudes during the day devoted to SHARAD calibration

A minimum of 4 crossovers are then required for a single measurement. Being 3 the minimum number of measurements to be averaged in order to have adequate accuracy, the minimum number of crossover to be used is 3 x 4.

The basic approach is anyway to collect data from all exploitable crossovers to provide data redundancy

Acquisition Definition for S/C configuration

Target areas: Crossover points (flat areas preferred)

Test Code: C3_01/02-xx_S

(01= reference configuration, 02= configuration to be characterized. xx from 01 on)

Class: S

S/C attitude: Nadir pointing

SS mode, Atten = 10 dB (TBC), 6 bit (TBC), presuming 4, open loop

Acquisition sequence: 90sec SS mode (+/- 45 sec around planned crossover)

Perform N times for each of the 4 configuration pairs

3.3.2. S/C Configurations Definition

With the term “S/C configuration”, we mean, here, the configuration of the S/C appendages, namely the solar array (SA) and the High Gain Antenna (HGA).

Each of them has two degrees of freedom, corresponding to the two articulation gimbals each of them have, with a total of 6 variables describing the appendages configuration.

The number of possible configuration which must be calibrated is, therefore, very high, in contrast with the limited time frame available to perform the calibration. Some simplification is therefore mandatory.

The first simplification is to decouple the HGA from the Solar Array: the assumption that their effects are independent is supported by the pattern measurement performed with a scaled mockup during the development tests. The antenna effect also appears to be much less significant than that related to the Solar Array.

The other is to drastically simplify the definition of SA configuration, based also on their frequency of occurrence during the mission. For the purpose of the initial calibration activities (with 1 day of S/C available), four main configurations have been considered, namely SA straight or tilted, normal to the deck or rotated.

They are described in detail below

Configuration for “calibration vs configuration”

Configurations:

- SA configurations will be named 0, 1, 3 and 4 (this for historical reasons...original configurations were more than 4)
- Antenna configuration: “I” (for “In-view”) and “O” (for “out-of-view”)

Calibration will be performed as follows:

Reference: 0-I

Target configurations: 1-I, 3-I, 4-I, 0-O.

For each configuration two ranges are defined:

- “applicability” range: the position of the SA and HGA gimbals will be used to define in which of the possible 8 configuration MRO is, in order to retrieve the appropriate correction factors from the calibration database.
- “Calibration” ranges: an interval of possible SA/HGA positions, much smaller than the “applicability” range, which is representative of an average behavior in the “applicability” range, and which will be used for calibration.

SA Configurations

	Applicability	Calibration
0	<ul style="list-style-type: none"> - SAPX IG: -40°to +40° - SAMX IG: -40°to +40° (and both inside +/- 35°) - OGA: -25°to + 25° 	<ul style="list-style-type: none"> - SAPX IG: 0° (+/- 10°) - SAMX IG: 0° (+/- 10°) - SAPX OG: 0° (+/-10°) - SAMX OG: 0° (+/-10°)
1	<ul style="list-style-type: none"> - OGA: -25°to + 25° - SAPX/SAMX IG: One of the two exceeding +/- 40° or both exceeding +/- 35° 	<ul style="list-style-type: none"> - SAPX IG: 50° (+/- 5°) - SAMX IG: 50° (+/- 5°) - SAPX OG: 0° (+/- 10°) - SAMX OG: 0° (+/- 10°)
3	configuration 0 but with OGA outside the envelope defined for configuration 0	<ul style="list-style-type: none"> - SAPX IG: 0° (+/- 10°) - SAMX IG: 0° (+/- 10°) - SAPX OG: 90° (+/-10°) - SAMX OG: 90° (+/-10°)
4	as configuration 1 but with OGA outside the envelope defined for configuration 1	<ul style="list-style-type: none"> - SAPX IG: 50° (+/- 5°) - SAMX IG: 50° (+/- 5°) - SAPX OG: 90° (+/-10°) - SAMX OG: 90° (+/-10°)

OGA = Average outer Gimbal Angle = (|SAPX IG| + |SAPX OG|)/2

HGA Configurations

“In-view” vs “out-of-view” definition

To quantify how much the HGA is “visible” from the SHARAD antenna, we define an “Antenna Visibility Factor” Af

$$A_f = A_v * A_m$$

Where:

$$A_v = \text{Antenna View Factor} = \cos(IG) * \sin(OG)$$

[representing the projection of the antenna dish on a plane parallel to the deck]

and

Am = Antenna Masking Factor:

$$IG < 90^\circ: A_m = 1$$

$$IG > 270^\circ: A_m = 1$$

$$90^\circ \leq IG \leq 270^\circ: A_m = (|IG - 180^\circ| * 90) * \cos OG$$

[note: antenna is masked when “flat” on the deck and behind it (IG 90° to 270°) – when it is “raised” it will unmask: this is accounted for (roughly) by the cos OG term]

	Applicability	Calibration
In-view	$Af > 0.5$	$Af > 0.85$ $-25^\circ < \text{HGA IG} < +25^\circ$ $-75^\circ < \text{HGA OG} < +75^\circ$
Out-of-view	$Af \leq 0.5$	$Af < 0.20$ $+165^\circ < \text{HGA IG} < +180^\circ$

Configurations Summary

The configuration to be verified are, therefore, the following:

- 1-I
- 3-I
- 4-I
- 0-O

with reference to configuration 0-I (“configuration zero”)

The two-way gain for configurations 1-O, 3-O and 4-O will then be computed by adding the HGA effect (difference between 0-O and 0-I) on top the results of configuration 1, 3 and 4 –I.

Configuration for “pattern calibration”

The pattern calibrations shall be done with the S/C in the same appendages configurations. It will be performed using the configuration that the S/C is normally assuming at 45°N (to minimize S/C workload), which is (roughly) the following:

- HGA IG: 14°
- HGA OG: 48°
- SAPX IG: 20°
- SAPX OG: 36°
- SAMX IG: 4°
- SAMX OG: 40°

In the (baseline) case that this calibration is performed on the northern hemisphere above 45°, in the ascending part of the orbit, it can be achieved simply freezing the SOLAR Array and HGA when crossing the 45°N.

3.4 Calibration Implementation

Calibration Time Slots

The planning for the execution of calibration foresees the first set of activities (those relevant to the reference function calibration) to be carried out downstream the instrument checkouts, possibly before the solar conjunction (Oct 6 2006 to Nov 10 2006), or immediately after.

The calibration for pattern and configuration will be performed during one dedicated “calibration day” (currently scheduled for early December, 2006) followed by the required repeated track passages 17 days later.

Other two days dedicated to calibration are envisaged to be available by early summer 2007: during this additional calibration slots possible acquisitions left over from the calibration day will be performed, and, more important, all the additional data (like calibration in intermediate configurations) which can be recognized as necessary following analysis of the first calibration run, will be collected.

Preconditions

The acquisitions for configuration and pattern calibration are planned to be performed using 6 bits resolution and a presuming 4. This combination has been selected as the best compromise between generated data volume and errors induced by the presuming.

Fig 3.4-1 depicts the limits for presuming (no radial velocity compensation) developed by the science team, assuming worst case radial velocity. Use of presuming 4 is possible almost anywhere but in very few areas.

To confirm the quality of data achievable with the selected acquisition defaults, before the calibration day, some surveys will be performed on sample areas, possibly using lower presuming and/or 8 bits (and simulating the effect of higher presuming/lower resolution on ground) in order to assess soundness of the selection and to modify the planned acquisition setting if needed.

Organization of the “Calibration Day”

During the “calibration day” (“C-day”), the S/C will operate exclusively for SHARAD, performing the required manouvres to achieve the appropriate configurations for the calibration acquisitions, with all other instrument being in not operative state (stand-by or OFF).

The organization of the “calibration day” has been assessed in detail, as have been all the required transition between configuration, with the aims of:

- fit all required acquisitions within the assigned time slot providing the maximum possible data redundancy
- minimize the manouvres required from the S/C
- avoid as much as possible manouvres during C-day + 17 (which is a nominal operation day with exclusion zones for SHARAD calibration), minimizing the interference with the science operation of the other instruments.

A map of Mars showing the orbit patterns during the calibration day and relevant crossovers is shown in fig 3.4-2 (a and b). Orbits 1 to 6 are used for reference passages on the cross-overs, while orbits 7 to 10 are used for the 4 configurations to be calibrated (one each orbit).

As results, at least 32 cross-overs will be generated (13 in each of the polar regions and 6 near the equator)

They have been assigned as follows:

- 5 to configuration 1 (I) (2 North, 2 South, 1 equator)
- 10 to configuration 3 (I) (4 North, 4 South, 2 Equator)
- 10 to configuration 4 (I) (4 North, 4 South, 2 Equator)
- 7 to configuration 0 (O) (3 North, 3 South, 1 equator)

This reflects the frequency with each configuration is used during operation (more frequent configurations have more calibration points)

Some parts of the orbits, not exploited for crossover, will be used for rolled acquisitions devoted to pattern calibration. In orbits 4, 5, and 6, no cross-overs are exploited during the ascending portion over the northern hemisphere: they are therefore used for pattern acquisitions at 0° pitch.

The appropriate appendages configuration will be, as detailed in 3.3.2, achieved by freezing the appendages at 45°N, ascending, before performing the rolls, and releasing them at the end of the sequence.

Following the calibration day, rolled acquisition will be performed, with the reference passes (with frozen appendages but with S/C in high-stability nadir pointing configuration) during "C-Day + 17". In this way no manoeuvres will be required outside the calibration day, except for the appendages to be frozen at 45°N, limiting the interference with other science operations to few "exclusion zones" during the SHARAD acquisitions.

All the mentioned acquisitions are possible commanding the instrument using nominal ITL.

Other 6 free slots of ¼ of orbit exist in the planning, which are potentially exploitable for the +/- 10° pitched acquisitions. Acquisition with pitched S/C is, anyway, a non nominal operation which is not compatible with ITL operation. Their exploitation is therefore not baseline.

If possible, it is recommended to add other two orbits (11 and 12) to be exploited for 2 acquisition for each of the two pitch values in the northern hemisphere (one ascending and one descending, keeping appendages frozen until the descending roll is complete). If this cannot be achieved, calibration with pitch ≠ 0 will be performed in the next calibration session.

Table 3.4-I provides a summary exploitable acquisitions.

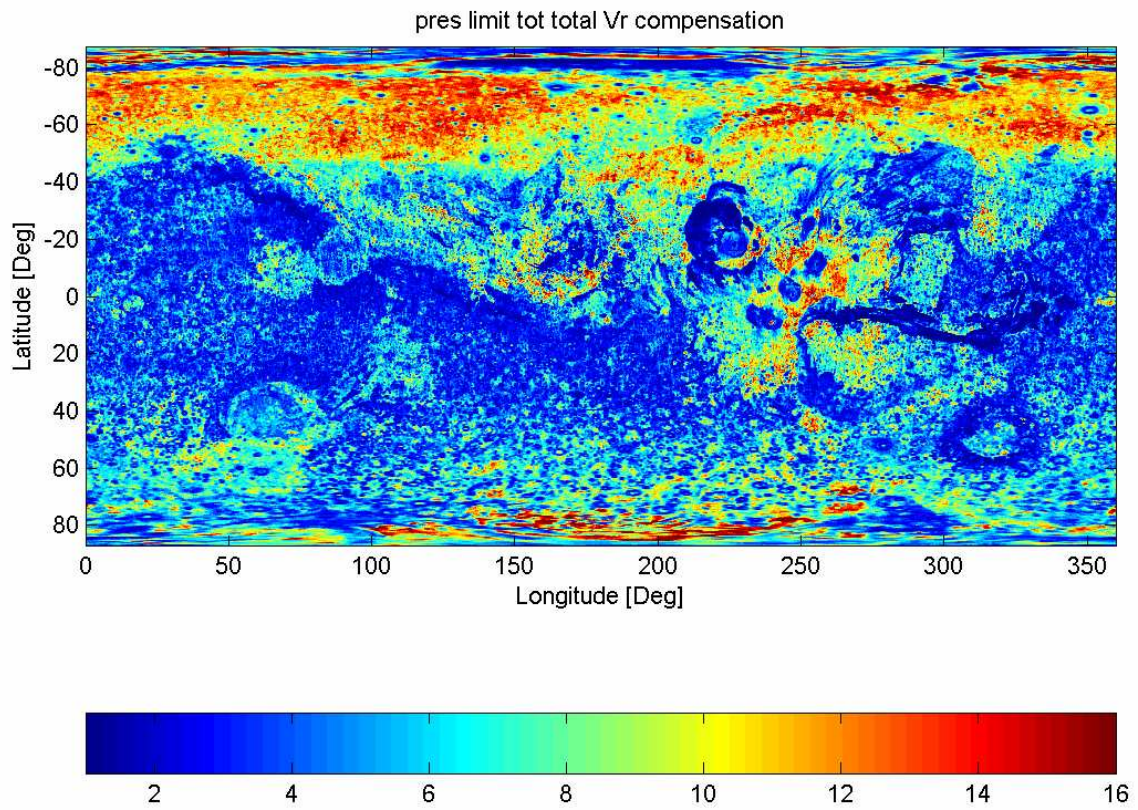


Fig 3.4-1 – computed presuming limits (worst case)

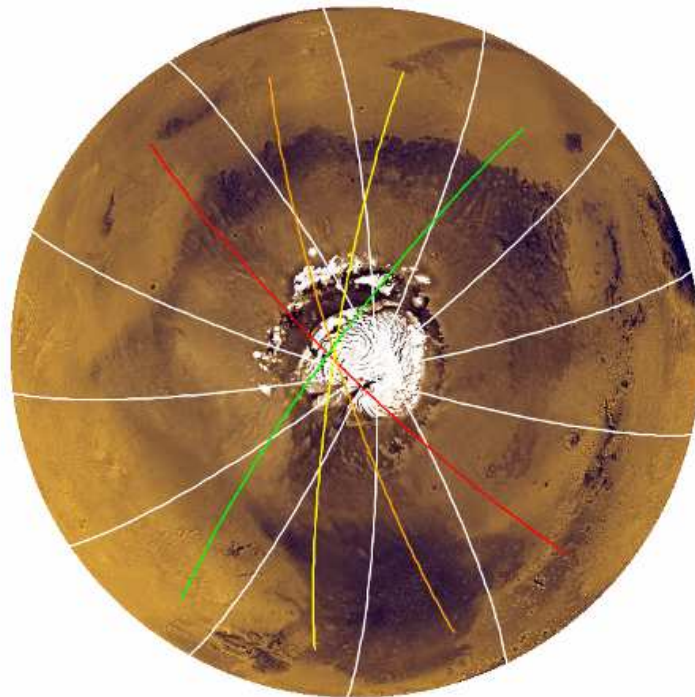
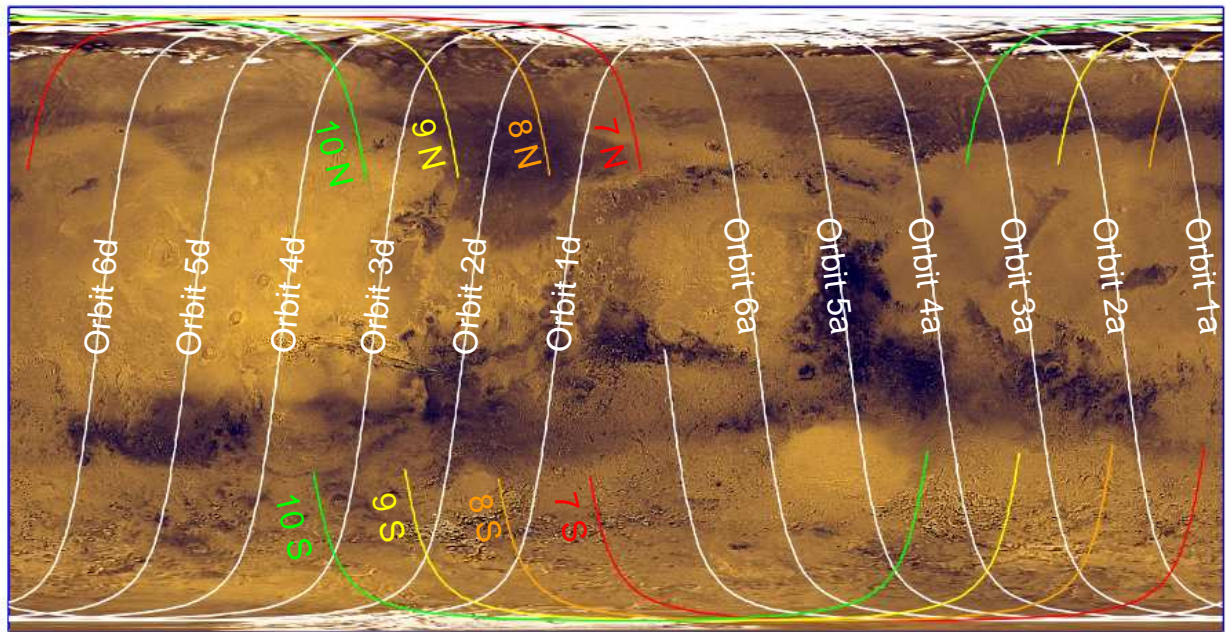


Fig 3.4-2 a, b – Crossovers during calibration day
(reference orbits in white)

ORBIT	a/d	lat	notes	config
1 a	N		crossover with orbit 8 d	reference
1 a	N		crossover with orbit 9 d	reference
1 d	N		crossover with orbit 7 a	reference
1 d	N-near EQUATOR		crossover with orbit 8 a	reference
1 d	S		crossover with orbit 8 a	reference
1 d	S		crossover with orbit 9 a	reference
1-2 a	N-near EQUATOR		crossover with orbit 8 d	reference
2 a	N		crossover with orbit 9 d	reference
2 a	N		crossover with orbit 10 d	reference
2 d	N		crossover with orbit 7 a	reference
2 d	N		crossover with orbit 8 a	reference
2 d	N-near EQUATOR		crossover with orbit 9 a	reference
2 d	S		crossover with orbit 9 a	reference
2 d	S		crossover with orbit 10 a	reference
2 a	S		crossover with orbit 7d	reference
2-3 a	N-near EQUATOR		crossover with orbit 9d	reference
3 a	N		crossover with orbit 10 d	reference
3 d	N		crossover with orbit 8 a	reference
3 d	N		crossover with orbit 9 a	reference
3 d	N-near EQUATOR		crossover with orbit 10 a	reference
3 d	S		crossover with orbit 10 a	reference
3 a	S		crossover with orbit 7d	reference
3 a	S		crossover with orbit 8d	reference
3-4 a	N-near EQUATOR		crossover with orbit 10d	reference
4 a	45-80°N		roll at 0°pitch	
4 d	N		crossover with orbit 9 a	reference
4 d	N		crossover with orbit 10 a	reference
4 d	S		opportunity for roll at non-zero pitch	
4 a	S		crossover with orbit 8 d	reference
4 a	S		crossover with orbit 9 d	reference
5 a	45-80°N		roll at 0°pitch	reference
5 d	N		crossover with orbit 10 a	reference
5 d	S		opportunity for roll at non-zero pitch	
5 a	S		crossover with orbit 9 d	reference
5 a	S		crossover with orbit 10 d	reference
6 a	45-80°N		roll at 0°pitch	
6 d	N		opportunity for roll at non-zero pitch	
6 d	S		opportunity for roll at non-zero pitch	
6 a	S		crossover with orbit 10 d	
7 a	N		crossover with orbit 1d	conf #1
7 a	N		crossover with orbit 2d	conf #1
7 d	N		opportunity for roll at non-zero pitch	
7 d	S		crossover with orbit 2 a	conf #1
7 d	S		crossover with orbit 3 a	conf #1
7 a	S		opportunity for roll at non-zero pitch	

Tab 3.4-I – Acquisitions sequence during calibration day (continued on next page)

ORBIT	a/d	lat	notes	config
7-8	a	N-near EQUATOR	crossover with orbit 1d	conf #1
8	a	N	crossover with orbit 2d	ref + ant OOV
8	a	N	crossover with orbit 3d	ref + ant OOV
8	d	N	crossover with orbit 1a	ref + ant OOV
8	d	N-near EQUATOR	crossover with orbit 2a	ref + ant OOV
8	d	S	crossover with orbit 3 a	ref + ant OOV
8	d	S	crossover with orbit 4 a	ref + ant OOV
8	a	S	crossover with orbit 1 d	ref + ant OOV
8-9	a	N-near EQUATOR	crossover with orbit 2 d	conf #3
9	a	N	crossover with orbit 3d	conf #3
9	a	N	crossover with orbit 4d	conf #3
9	d	N	crossover with orbit 1a	conf #3
9	d	N	crossover with orbit 2a	conf #3
9	d	N-near EQUATOR	crossover with orbit 3a	conf #3
9	d	S	crossover with orbit 4 a	conf #3
9	d	S	crossover with orbit 5 a	conf #3
9	a	S	crossover with orbit 1 d	conf #3
9	a	S	crossover with orbit 2 d	conf #3
9-10	a	N-near EQUATOR	crossover with orbit 3d	conf #4
10	a	N	crossover with orbit 4d	conf #4
10	a	N	crossover with orbit 5d	conf #4
10	d	N	crossover with orbit 2a	conf #4
10	d	N	crossover with orbit 3a	conf #4
10	d	N-near EQUATOR	crossover with orbit 4a	conf #4
10	d	S	crossover with orbit 5 a	conf #4
10	d	S	crossover with orbit 6 a	conf #4
10	a	S	crossover with orbit 2 d	conf #4
10	a	S	crossover with orbit 3 d	conf #4
11	a	N	roll at -10°pitch	nice-to-have only
11	d	N	roll at -10°pitch	nice-to-have only
12	a	N	roll at +10°pitch	nice-to-have only
12	d	N	roll at +10°pitch	nice-to-have only

Tab 3.4-I – Acquisitions sequence during calibration day (continued)

3.5 Calibration Cases

The list of acquisitions is provided in the table below

REFERENCE RESPONSE ACQUISITION

This phase of the calibration foresees individual acquisitions to be performed over flat areas – S/C in reference configuration and nadir pointing. No other constraints.

Step	Acq code	Description	Class	Date	Orbit	Surface characteristics	Acq. sequence	S/C Conf	S/C attitude	Data Volume	Remarks
1	C1_01-01_S	Active radiometric cal in Ref conditions	S			Flat Area	20 sec in SS 8 bit – No presum Gain ctrl = 10dB Auto-scale = OFF Open loop trk	Reference	Nadir Pointing	408 Mbit	
1	C1_01-02_S	Active radiometric cal in Ref conditions	S			Flat Area	20 sec in SS 8 bit – No presum Gain ctrl = 10dB Auto-scale = OFF Open loop trk	Reference	Nadir Pointing	408 Mbit	
1	C1_01-03_S	Active radiometric cal in Ref conditions	S			Flat Area	20 sec in SS 8 bit – No presum Gain ctrl = 10dB Auto-scale = OFF Open loop trk	Reference	Nadir Pointing	408 Mbit	
1	C1_01-04_S	Active radiometric cal in Ref conditions	S			Flat Area	20 sec in SS 8 bit – No presum Gain ctrl = 10dB Auto-scale = OFF Open loop trk	Reference	Nadir Pointing	408 Mbit	
1	C1_01-05_S	Active radiometric cal in Ref conditions	S			Flat Area	20 sec in SS 8 bit – No presum Gain ctrl = 10dB Auto-scale = OFF Open loop trk	Reference	Nadir Pointing	408Mbit	

Step	Acq code	Description	Class	Date	Orbit	Surface characteristics	Acq. sequence	S/C Conf	S/C attitude	Data Volume	Remarks
1	C1_01-06_S	Active radiometric cal in Ref conditions	S			Flat Area	20 sec in SS 8 bit – No presum Gain ctrl = 10dB Auto-scale = OFF Open loop trk	Reference	Nadir Pointing	408Mbit	

ANTENNA PATTERN CALIBRATION

This phase of the calibration requires to perform two separate acquisitions on the same ground track at 17 days distance. The need for a long acquisition (370 sec) all performed on a flat area would suggest as ideal target the 60°N-80°N plain region. A roll manoeuvre is required during the acquisition, with different pitch angles.

A start of the roll manoeuvre synchronized with the start of the acquisition within 3-4 sec is needed

Step	Acq code	Description	Class	Date	Orbit	Surface characteristics	Acq. sequence	S/C Conf	S/C attitude	Data Volume	Remarks
2	C2_01-01_S_01	Reference for acquisition C2_02-01_S_01	S			+45°N to +85°N flat area	SS mode, Atten = 10 dB, 6 bit, presuming 4, open loop 490 sec, alternating 10 sec SS and 20 sec wait. Ends with 10 sec SS	As frozen at 45°N, ascending	Nadir Pointing	3463 Mbit	Track "A"
2	C2_01-01_S_02	Reference for acquisition C2_02-01_S_02	S			+45°N to +85°N flat area	As above	As frozen at 45°N, ascending	Nadir Pointing	3463 Mbit	Track "B"
2	C2_01-01_S_03	Reference for acquisition C2_02-01_S_03	S			+45°N to +85°N flat area	As above	As frozen at 45°N, ascending	Nadir Pointing	3463 Mbit	Track "C"
2	C2_02-01_S_01	Rolled acquisition at -10°pitch	S			+45°N to +85°N flat area	As above	As frozen at 45°N, ascending	Pitch -10° Roll 10°/min	3463 Mbit	Track "A"
2	C2_02-01_S_02	Rolled acquisition at -10°pitch	S			+45°N to +85°N flat area	As above	As frozen at 45°N, ascending	Pitch -10° Roll 10°/min	3463 Mbit	Track "B"
2	C2_02-	Rolled acquisition at	S			+45°N to	As above	As frozen	Pitch -10°	3463	Track "C"

Step	Acq code	Description	Class	Date	Orbit	Surface characteristics	Acq. sequence	S/C Conf	S/C attitude	Data Volume	Remarks
	01_S_03	-10°pitch				+85°N flat area		at 45°N, ascending	Roll 10°/min	Mbit	
2	C2_01-02_S_01	Reference for acquisition C2_02-02_S_01	S			+45°N to +85°N flat area	As above	As frozen at 45°N, ascending	Nadir Pointing	3463 Mbit	Track "D"
2	C2_01-02_S_02	Reference for acquisition C2_02-02_S_02	S			+45°N to +85°N flat area	As above	As frozen at 45°N, ascending	Nadir Pointing	3463 Mbit	Track "E"
2	C2_01-02_S_03	Reference for acquisition C2_02-02_S_03	S			+45°N to +85°N flat area	As above	As frozen at 45°N, ascending	Nadir Pointing	3463 Mbit	Track "F"
2	C2_02-02_S_01	Rolled acquisition at 0°pitch	S			+45°N to +85°N flat area	As above	As frozen at 45°N, ascending	Pitch 0° Roll 10°/min	3463 Mbit	Track "D"
2	C2_02-02_S_02	Rolled acquisition at 0°pitch	S			+45°N to +80°N flat area	As above	As frozen at 45°N, ascending	Pitch 0° Roll 10°/min	3463 Mbit	Track "E"
2	C2_02-02_S_03	Rolled acquisition at 0°pitch	S			+45°N to +85°N flat area	As above	As frozen at 45°N, ascending	Pitch 0° Roll 10°/min	3463 Mbit	Track "F"
2	C2_01-03_S_01	Reference for acquisition C2_02-03_S_01	S			+45°N to +85°N flat area	As above	As frozen at 45°N, ascending	Nadir Pointing	3463 Mbit	Track "G"
2	C2_01-03_S_02	Reference for acquisition C2_02-03_S_02	S			+45°N to +85°N flat area	As above	As frozen at 45°N, ascending	Nadir Pointing	3463 Mbit	Track "H"
2	C2_01-03_S_03	Reference for acquisition C2_02-03_S_03	S			+45°N to +85°N flat area	As above	As frozen at 45°N, ascending	Nadir Pointing	3463 Mbit	Track "I"

Step	Acq code	Description	Class	Date	Orbit	Surface characteristics	Acq. sequence	S/C Conf	S/C attitude	Data Volume	Remarks
2	C2_02-03_S_01	Rolled acquisition at +10°pitch	S			+45°N to +85°N flat area	As above	As frozen at 45°N, ascending	Pitch +10° Roll 10°/min	3463 Mbit	Track "G"
2	C2_02-03_S_02	Rolled acquisition at +10°pitch	S			+45°N to +85°N flat area	As above	As frozen at 45°N, ascending	Pitch +10° Roll 10°/min	3463 Mbit	Track "H"
2	C2_02-03_S_03	Rolled acquisition at +10°pitch	S			+45°N to +85°N flat area	As above	As frozen at 45°N, ascending	Pitch +10° Roll 10°/min	3463 Mbit	Track "I"

CALIBRATION VS S/C CONFIGURATION

This calibration phase takes advantage of crossover points to calibrate the antenna gain vs the S/C configuration (SA and HGA).

For each crossover generated during the calibration day, a pair of acquisitions (one during reference orbit, one during pass in target configuration) shall be performed.

Configurations for the different crossovers shall be in accordance to tab 3.4-I

Detailed sequence to be generated in accordance to the ephemeris relevant to calibration day when available

Step	Acq code	Description	Class	Date	Orbit	Surface characteristics	Acq. sequence	S/C Conf	S/C attitude	Data Volume	Remarks
3	C3_01-xx_S_01	Reference acquisition for C3_02-xx_S_01	S			Crossover on flat area	SS mode, Atten = TBD, 8 bit, no presuming, open loop Acquisition sequence: 90 sec SS mode	Reference	Nadir Pointing	351 Mbit	Crossover "xx"
3	C3_02-xx_S_01	Acquisition at target configuration	S			Crossover on flat area	As above	"target"	As above	351 Mbit	Crossover "xx"

3.6 Calibration Data Processing and Handling

3.6.1 Passive Radiometric Calibration

Scope of this test is to measure the amplitude frequency response of the Rx-chain , included antenna. The inputs for the processing will be:

- Galactic Noise Model. $A_n(f)$ indicates the amplitude spectrum of the Galactic noise.
- Rx-gain versus frequency @ different temperatures ($A_{Rx}(f)$).
- Measured amplitude spectrum ($A(f)$).

The measured amplitude spectrum can be expressed as:

$$A(f) = A_{Rx}(f) + A_{Ant}(f) + A_n(f)$$

Where $A_{Ant}(f)$ is the amplitude frequency response of the antenna. The knowledge of $A(f)$ and $A_n(f)$ allows to obtain

$$A_{Rx}(f) + A_{Ant}(f) = A(f) - A_n(f).$$

If the noise measurement will be performed @ a temperature different from 20°C, we can use data acquired during TV tests, in order to normalize amplitude data to the reference temperature of 20°C:

$$\Delta A_{Rx}(f)_{@T^{\circ}C} = A_{Rx}(f)_{@T^{\circ}C} - A_{Rx}(f)_{@20^{\circ}C},$$

then

$$A_{Rx}(f)_{@T^{\circ}C} + A_{Ant}(f) = A(f)_{@T^{\circ}C} - A_n(f) \Rightarrow A_{Rx}(f)_{@20^{\circ}C} + A_{Ant}(f) = A(f)_{@T^{\circ}C} - A_n(f) - \Delta A_{Rx}(f)_{@T^{\circ}C}$$

Note that the antenna is assumed to be invariant versus temperature.

Resuming, the following steps shall be performed:

- 1) Loading raw data;
- 2) FFT of the raw data;
- 3) Square modulus of the Fourier transformed data;
- 4) Average on 3 seconds of acquisition (2100 pris @ Nom. PRF);
- 5) Fitting of the Power Spectrum (PwS) obtained @ step 4;
- 6) Remove Galactic Noise contribute ($A_n(f)$);
- 7) Read the Rx temperature from Engineering Telemetries;
- 8) Estimate amplitude variation respect to the nominal temperature (20°C);

3.6.2 Active Radiometric Calibration

The active calibration can be split in three main steps:

- Nominal Reference Acquisitions;
- Pattern Calibration;
- Calibration versus Spacecraft Configuration;

Nominal Reference Conditions

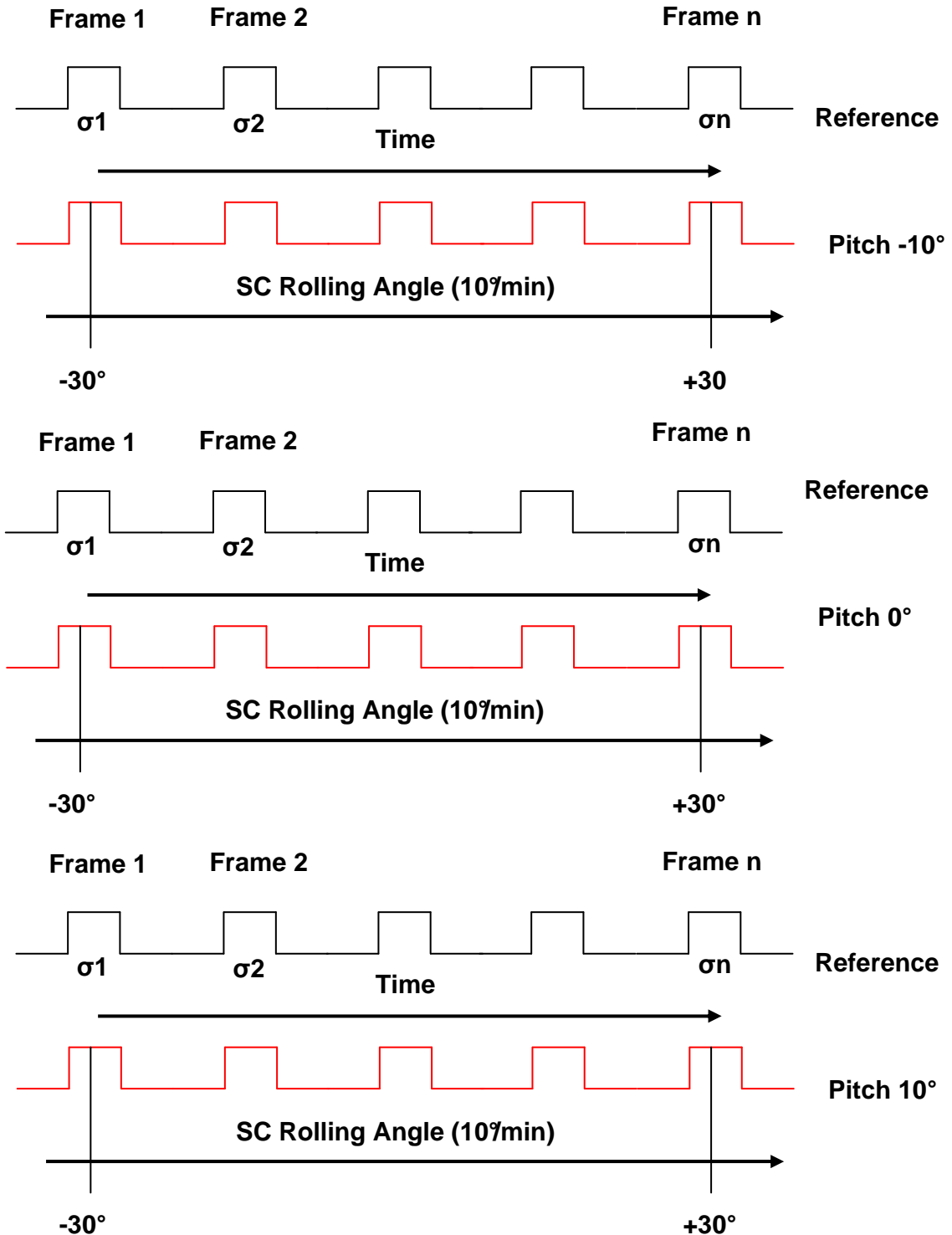
This test will be performed on flat area; therefore the returned signal will be similar to the echo from a single point target: this simplifies the amplitude/phase ripple calculation. The following steps shall be performed:

- 1) Loading raw data;
- 2) Base-band conversion;
- 3) Spurious signals removal (optional);
- 4) Phase compensation due to possible shift of the Rx-window opening time between blocks (negligible on flat area);
- 5) Short-Time average of N pris (100 echoes are more than sufficient);
- 6) Fast Fourier Transform of the averaged signal ($S(f)$);
- 7) Generation of an ideal chirp with the same characteristics of the chirp acquired by SHARAD;
- 8) Base-band conversion of the ideal chirp;
- 9) Fast Fourier Transform of the ideal chirp ($R(f)$);
- 10) Inverse Filter Generation starting from $R(f)$: $R_I(f) = 1/R(f)$;
- 11) Multiplication in the frequency domain between $S(f)$ and the conjugate of $R_I(f)$:
 $S_C(f) = S(f) \cdot \text{conj}(R_I(f))$;
- 12) Amplitude Ripple Calculation:
 - a) we consider $S_{CB}(f) = S_C(f)$ with $f \in [-B/2; B/2]$, where B is the SHARAD bandwidth;
 - b) $\text{Amp}(f) = |S_{CB}(f)| / \text{mean}[|S_{CB}(f)|]$;
 - c) Read the Rx temperature from Engineering Telemetries;
 - d) Save amplitude variation vs nominal temperature;
- 13) Phase Ripple Calculation:
 - a) we consider $S_{CB}(f) = S_C(f)$ with $f \in [-B/2; B/2]$, where B is the SHARAD bandwidth;
 - b) Find the coefficients of a polynomial $P(f)$ of degree 1 that fits $\angle S_{CB}(f)$;
 - c) Evaluate the polynomial $P(f)$ in $f \in [-B/2; B/2]$: $Y(f) = \text{polyval}(P, f)$;
 - d) $\text{Ph}(f) = \angle S_{CB}(f) - Y(f)$;
 - e) Save phase variation vs nominal temperature;

Pattern Calibration

The pattern characterization is performed by measuring the nadir echo at different spacecraft attitudes.

In the figure below, we can find the sequence of measurements for pattern calibration:



Resuming the test foresees three couple of measurements repeated three times so to average the results with consequent improved accuracy.

- Reference Acquisition for -10° of Pitch (Nadir Pointing);
- Acquisition with fixed Pitch (-10°) and SC rolling between -30° and $+30^\circ$ with rate=10%/min;
- Reference Acquisition for 0° of Pitch (Nadir Pointing);
- Acquisition with fixed Pitch (0°) and SC rolling between -30° and $+30^\circ$ with rate=10%/min;
- Reference Acquisition for $+10^\circ$ of Pitch (Nadir Pointing);
- Acquisition with fixed Pitch ($+10^\circ$) and SC rolling between -30° and $+30^\circ$ with rate=10%/min;

Each pair of measurements shall be done in the same zone of Mars (i.e. the same frames are covered during reference and rolled acquisition). In general, each zone has a different radar-cross section (σ). Remember that the magnitude of the received echo depends by σ .

A magnitude measurement of the range compressed echo shall be done for each frame. This value must be compared with the one obtained during the reference acquisition at the same frame. At the end of the analysis, the following table shall be filled:

Frame	Acq. Type	Echo-Magnitude	Pitch	Roll	Delta Reference vs
1	REF. for Pitch -10°	250	N.A.	N.A.	N.A.
1	ROLLED	280.5046	-10°	-30°	0.5 (dB)
2	REF. for Pitch -10°	251	N.A.	N.A.	N.A.
2	ROLLED	281.6220	-10°	-25°	0.5 (dB)
3	REF. for Pitch -10°	260	N.A.	N.A.	N.A.
....
1	REF. for Pitch 0°	250	N.A.	N.A.	N.A.
1	ROLLED	280.5046	0°	-30°	0.5 (dB)

The following steps shall be performed:

- 1) Loading raw data;
- 2) Base-band conversion;
- 3) Spurious signals removal (optional);
- 4) Phase compensation due to possible changes of the Rx-window opening time (negligible on flat area);
- 5) Short-Time average of N pris (100 echoes are more than sufficient);
- 6) Range compression, using inverse filter and Hanning weighting function;
- 7) Calculation of the magnitude of the square-detected-compressed echo;
- 8) Save the measured echo magnitude;
- 9) Evaluate the difference respect to the reference acquisition @ the same frame.

Calibration vs S/C configuration

The antenna gain depends by the S/C configuration. For this reason a calibration of the antenna gain at nadir is also required for different combination of solar array and HGA position.

To perform this calibration it is possible to exploit cross-overs, performing the first acquisition in the “reference” spacecraft configuration and in one of the other configurations to be characterized. Cross-over guarantee no change in radar-cross section between one of the configurations and the corresponding reference acquisition.

At the end of the analysis, the following table shall be filled:

Cross-over Point	Acq. Type	Echo-Magnitude	Solar Array position	HGA position	Delta Reference vs
1	REF. for config.#1	250	N.A.	N.A.	N.A.
1	CONF.#1	280.5046	See Figure 3.3-2 config.#1	See Figure 3.3-2 config.#1	0.5 (dB)
2	REF. for config.#2	251	N.A.	N.A.	N.A.
2	CONF.#2	281.6220	See Figure 3.3-2 config.#2	See Figure 3.3-2 config.#2	0.5 (dB)
3	REF. for config.#3	260	N.A.	N.A.	N.A.
....
4	REF. for config.#N	250	N.A.	N.A.	N.A.
4	CONF.#N	280.5046	See Figure 3.3-2 config.#N	See Figure 3.3-2 config.#N	0.5 (dB)

The following steps shall be performed:

- 1) Loading raw data;
- 2) Base-band conversion;
- 3) Spurious signals removal (optional);
- 4) Phase compensation due to possible changes of the Rx-window opening time (negligible on flat area);
- 5) Short-Time average of N PRIs (100 echoes are more than sufficient). Considering NT the total number of pris, we can divide the acquisition in $N_{sb} = \text{fix}(NT/N)$ sub-blocks of N pris.
- 6) Range compression of each averaged sub-block, using inverse filter and Hanning weighting function;
- 7) Calculation of the magnitude of the square-detected-compressed echo;
- 8) Mean value between blocks of the magnitude echo;
- 9) Save the mean echo magnitude;
- 10) Evaluate the difference respect to the value obtained in reference acquisition.

[Note: all amplitude data shall be normalized to the reference temperature of 20°C, using the Tx power and Rx gain variation vs temperature characterized on-ground]

4 CALIBRATION OF OPERATIONAL DATA

4.4 General Organization

Reference function

The reference function will be stored as phase and amplitude deviation over frequency wrt to an ideal chirp, normalized to +20°C.

The variation of the above correction vs temperature (difference wrt 20 °C phase/amplitude errors) as derived from ground tests, is recorded in the temperature database.

Passive Radiometric correction

The value of $Grx \cdot GA$ as a function of frequency will be used to correct the radiometric data.

Active Radiometric correction

The value for "reference" $Ptx \cdot Grx \cdot GA^2$, as derived from calibration acquisition (normalized to the 20°C temperature according to the tests performed on ground), is stored in the system.

Before being used for correcting the data amplitude, this data shall be corrected for:

- pattern, if the observation is performed Off-Nadir
- S/C configuration, if the S/C configuration is different from the reference one
- Temperature variation of Ptx and Grx , if the SEB temperature is different from the reference temperature

4.5 Calibration Database Structure

Calibration data will be arranged, for retrieval and application to science data, into:

- reference function definition [$@ +20 \text{ °C}$] and $Ptx \cdot Grx \cdot GA^2 @ 20 \text{ °C}$
- temperature database [(variation wrt $+20 \text{ °C}$ of $Ptx \cdot Grx$) and delta phase/amplitude errors vs temperature]
- pattern database [GA^2 vs pitch, roll angle, normalized to 0 dB at nadir, in the reference configuration]
- configuration database [GA^2 at nadir vs S/C configuration, normalized to 0 dB at Ref S/C configuration]
- $Grx \cdot GA$ vs frequency (for passive radiometric calibration)

4.6 Application of Calibration to Data

Correlation reference function:

- from Rx and TFE Temp telemetries, identified the applicable temperature range.

- Add, point to point, the delta phase/amplitude from the corresponding record of the temperature database to the reference function definition
- Apply the phase/amplitude law achieved in this way to a theoretical chirp to obtain the reference to be used for correlation.

Active radiometric:

- Start from reference value of $P_{tx} G_{rx} GA^2$
- Add variation according to temperature
- Add variation according to S/C attitude from pattern database
- Add variation according to S/C configuration from configuration database

4.7 Periodical Rechecks

In order to characterize possible drifts in the transmitter power and/or receiver gain, repetition of measurement (3 sec acquisition min) in at least 3 reference areas, in the same conditions (S/C configuration, attitude) shall be performed at least every 6 months in order to monitor power and gain trends.

No verification of pattern and configuration sensitivity is required not being the antenna pattern expected to be sensitive to ageing.

