AIM-Space Cryocooler Programs

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ABSTRACT

As an experienced supplier of tactical IR-technology, AIM is now involved in several IR space programs covering applications at different wavelengths.

To the meet demands for compactness and weight, AIM has focused on Integrated Detector Cooler Assemblies (IDCA). This approach provides for the elimination of the detector - cooler interfaces on the customer side. Cryocoolers used in the IDCA configuration are based upon the designs of the AIM Flexure Bearing Moving Magnet family. Due to volume production, all relevant components and manufacturing processes have achieved a high level of maturity and thus enabling accurate reliability prediction.

To apply standard processes for the fabrication of space IDCA, the cold finger needs to fit into a standard dewar interface. Therefore, the pulse-tube cold finger was developed with standard Stirling-type dimensions. To retain maximum flexibility, the cold finger is designed for use with different sizes of flexure bearing compressors. The buffer volume and inertance tube are optimized for individual compressor types and performance requirements.

The qualification activities for two different space programs are ongoing and their respective results will be presented in this paper. Furthermore, detailed performance characteristics at variable conditions will be presented.

INTRODUCTION

The demand for infrared imaging in space has increased significantly over the last decade. Particular emphasis has been placed upon civilian applications such as weather forecasting, geological observations and atmospheric monitoring. Depending on the application, imaging systems need to be sensitive to a specific wavelength, later referred to as the spectral range. Whilst SWIR systems employ detectors to capture “Short Wave Infrared”, MWIR and LWIR systems are sensitive to “Medium-” and “Long Wave Infrared”. Table 1 addresses the application of the spectral range with their respective purpose.

AIM as a leading manufacturer of IR-detectors and modules has recently been chosen as the supplier for two infrared space imagers: one to be incorporated in the Korean Multipurpose Satellite referred to as KOMPSAT-3A and the other to be integrated into the German Environmental Mapping and Analysis Program (EnMAP). The KOMPSAT-3A, and EnMAP imagers operate at different spectral ranges, necessitating different detector temperatures. The following sections will introduce the above-mentioned programs and describe a suitable cooling arrangement.

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Table 1. Spectral range and applications for different IR-Systems

IR designation	Spectral range [nm]	Typical Sensor Temp [K]	Typical mission profile	remark
NIR	700-1000	>180	Earth observation & Environmental mapping	reflected sun radiation dominates image
SWIR	1000-2500	120…180		reflected sun radiation affects image
MWIR	3000-5000	80…120	hot spot detection (urban heat concentration and forest fire)	negligible influence of sun radiation
LWIR	7000-15000	<80	Weather forecast & detection of trace gases	No influence of sun reflection

SPACE PROGRAMS

KOMPSAT-3A

This module is intended to operate at an altitude of approximately 700 km (lower earth orbit) capturing geospatial, environmental and agricultural information by scanning the earth's surface in a "push broom" mode. The satellite incorporates an individual detector for both IR and panchromatic spectral range. The infrared imager operates within a wavelength of 3,000 to 5,000 nm at high spatial and thermal resolution. The sensing array is made of Mercury-Cadmium-Telluride (MCT) and hybridized with the Read-Out-Integrated-Circuit (ROIC) forming the Focal Plane Array (FPA). With a total heat load of 800 mW, the KOMPSAT MWIR MCT detector is to be operated at 80 K. For those given conditions, the AIM SF400 compressor was chosen in conjunction with a ½" pulse-tube cold finger.

EnMAP

Under the auspices of the German hyperspectral satellite EnMAP, AIM is developing the dedicated 1,024x256 MCT-Focal Plane Array push-button imaging detector module for the SWIR spectral range. The EnMAP-satellite will operate at an altitude of 643 km and scan the earth from a polar orbit at a spatial resolution of 30 x 30 meters with a 10 nm radiometric resolution from 900 nm to 2450 nm. The main objective of EnMAP is to investigate a wide range of ecosystem parameters encompassing agriculture, forestry, soil and geological environments, coastal zones and inland waters. This will significantly increase the understanding of the coupled biospheric and geospheric processes and thus, methods can be developed to improve the sustainability of our vital resources. Because of the noise sensitivity of a SWIR detector is comparatively low, the system can be operated at comparatively high temperatures for a cryogenic application and has smaller cooling requirements. The EnMAP detector dewar has a thermal load of approximately 750 mW at 150 K. For this program, the SF100 compressor with a ¼" pulse-tube cold finger is used. Table 2 presents the cryocooler configurations for the AIM space programs.

TACTICAL LONG LIFE COOLERS

Split Linear Flexure Bearing Cooler (SF-series)

The general requirements for long-life performance stability and reliability are satisfied by the AIM Flexure Bearing cooler series. The common cooler design prevents piston coating abrasion by providing a radially stiff piston suspension which permits steady concentric movement without random contact to the surrounding assemblies.

Considering the contamination of the working gas by outgassing organic material, the compressor was designed so that all materials with outgassing potential are separated from the working fluid. AIM compressors of the SF-family use a moving magnet design, which isolates the coil, a major contaminator, to be separated from the working gas.

Table 2. Overview of AIM space programs

Program	EnMAP	KompSAT 3A
T_{Cold}	150K	80K
$T_{Ambient}$	25°C	35°C
Compressor	SF100	SF400
Coldfinger	1/2" PT	1/2" PT
Heat load	800mW	850mW
$P_{AC,ma;\ BOL}$	19.5 W_{AC}	52 W_{AC}
Cooler mass	2.1 kg	3.5 kg
Vibration output	<1.5N_{RMS}	<2.5N_{RMS}

Figure 1 shows the schematic design of the SF100 and the SF400 compressor. The SF100 compressor was originally designed as a form fit function replacement for a "One Watt class tactical Linear cooler (OWL) and fulfills all requirements of the OWL specification with Stirling coldfinger. In this configuration the cooler achieves 20,000 hr MTTF. This mean time to failure value is caused by the wear-out of the Stirling expander surface only. The compressor does not incorporate a relevant lifetime-limiting mechanism and is thus suitable to meet MTTF figures in excess of 50,000 hr.

Pulse-Tube Coldfinger

When using a flexure bearing Stirling-type cooler, the coldfinger is the lifetime-limiting component. Due to its moving displacer and mechanical abrasion, the achievable cooling capacity of the Stirling coldfinger degrades over time. Additionally, the displacer significantly contributes to the cooler's exported vibrations. Without any moving parts, pulse-tube cold fingers provide for an unlimited lifetime, theoretically, by having neither abrasion nor contamination potential. In combination with the Flexure Bearing compressor, pulse-tube coolers achieve lifetimes above 50,000 hr MTTF.

AIM has developed a pulse-tube coldfinger in the ½" standard dimension as used in several tactical cooler programs (Figure 2). The pulse-tube coldfinger was developed to fit into an AIM developed dewar. All dimensions and materials used at the dewar interface are identical to the Stirling type coldfinger. Consequentially all production processes, well known from Stirling-type batch production, can be used to build up the detector dewar assembly.

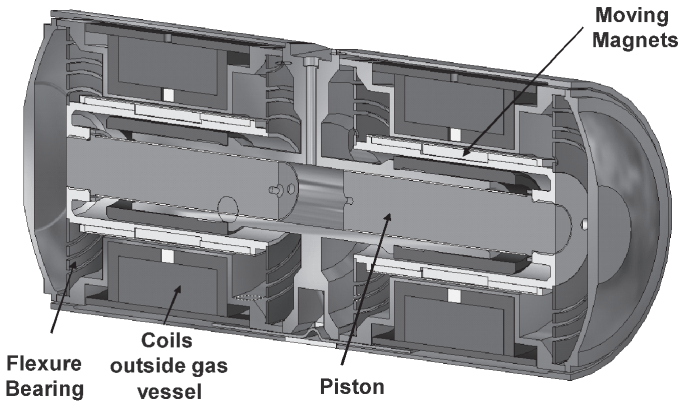

Figure 1. Flexure Bearing compressor setup (principle sketch)

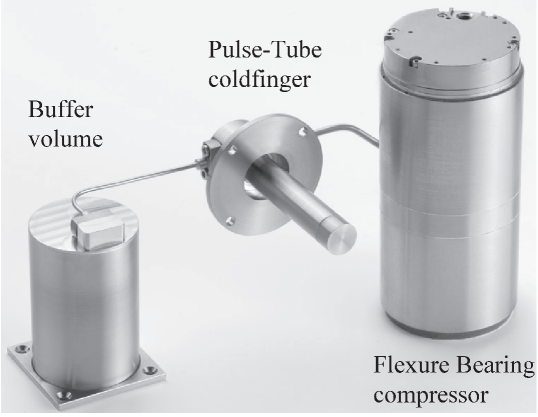

Figure 2. Flexure Bearing compressor SF100B with ½" Pulse-Tube coldfinger and buffer volume with integrated Inertance tube.

Space Capability for Cryocoolers

The AIM Flexure Bearing cooler series provides for high reliability and long life performance. The experience of more than one hundred SF100 cooler units provides the basis for the development of a space-qualified cryocooler family to be offered at a reasonable cost. Reliability and long life performance are supported by life time testing of several SF100 Stirling and pulse-tube coolers. Tested coolers demonstrate constant cool-down and steady state performance over a duration of 20,000 operating hours. Life test evaluation is ongoing.

The internal compressor design (coil, magnet, cylinder sleeve, piston, spring, etc.) of the tactical version remains unchanged for space applications. However, further quality assuring steps are added to the standard manufacturing processes and test procedures to fulfill the higher standards for space applications.

For the space versions of the compressor and the pulse-tube coldfinger, several external construction changes have been made to meet the space interface requirements. Figure 3 shows a comparison of the standard SF400 compressor housing with pulse-tube and the modified space-ready chassis. The compressor and the pulse-tube warm end provide surfaces for heat pipe mounting. The new housing also includes the mechanical interface for the mounting the compressor to the base plate of the satellite.

SPACE CRYOCOOLER PERFORMANCE

The cryocooler performance specifications are already given in the space programs section. For both programs, a pre-qualification has already been performed to assure product adequacy and compatibility. The compressor, the pulse-tube warm end and also the buffer volume were connected to a thermal interface assuring the missions environmental temperature conditions.

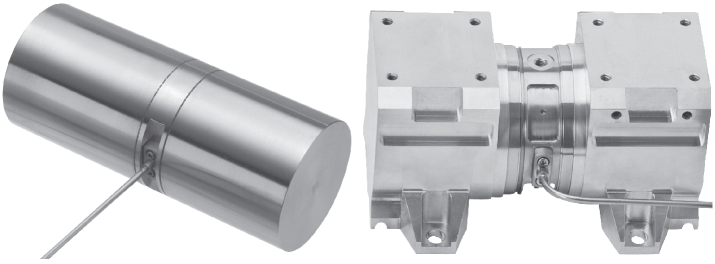

Figure 3. SF400 standard compressor housing (left), space modified housing (right)

In Figure 4, the cooling capacity of the SF100 is plotted over input power at different cold head temperatures for T_{amb}=25°C. The power consumption at the nominal operating point is 17.5 W_{DC}. For the tests, standard cooler control electronics were used.

In Figure 5, performance data for the SF400 driven by an AC power source is shown for different cold tip temperatures.

In general, space applications demand very low vibration output levels. EnMAP and KOMPSAT have specified vibration output levels in the typical range of tactical cryocoolers. Therefore no vibration control electronics are needed. Figure 6 shows the vibration output signals of the standard SF100 compressor with a pulse-tube coldfinger for all three dimensions.

The graph of the compressor longitudinal axis shows the vibration output distribution with signal peaks at the compressor operating frequency and higher harmonics. With a peak value less than 1 N_{RMS}, the standard SF100 Pulse-Tube cooler clearly meets the requirements for the EnMap. The vibration of the coldfinger longitudinal axis is characterized by noise without any additional peaks at operating frequency or the higher harmonics resulting from the coldfinger. For the qualification and the flight model, motor halves of the compressor will be matched according to their driving forces, which will reduce the vibration output level.

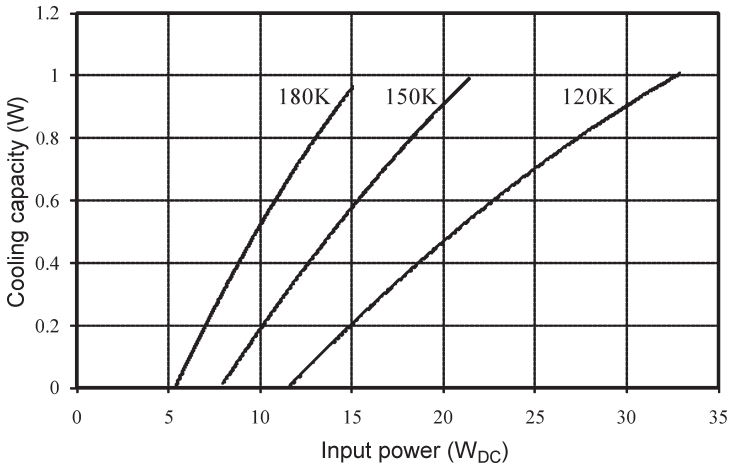

Figure 4. Performance data for SF100 at stated cooling temperatures

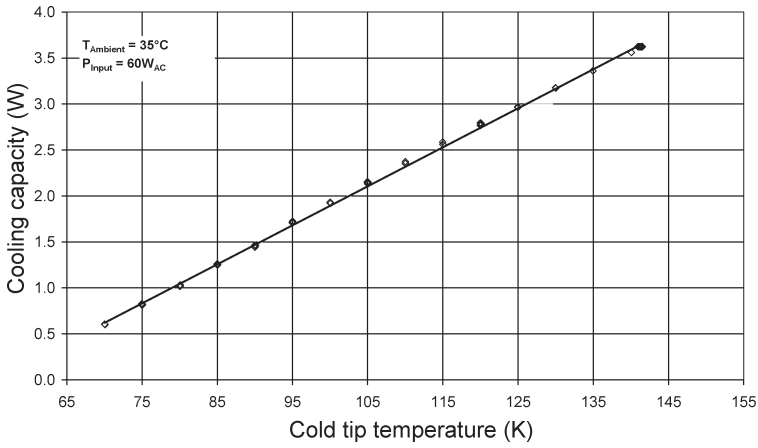

Figure 5. Performance of SF400 with 60 W_{AC} input power

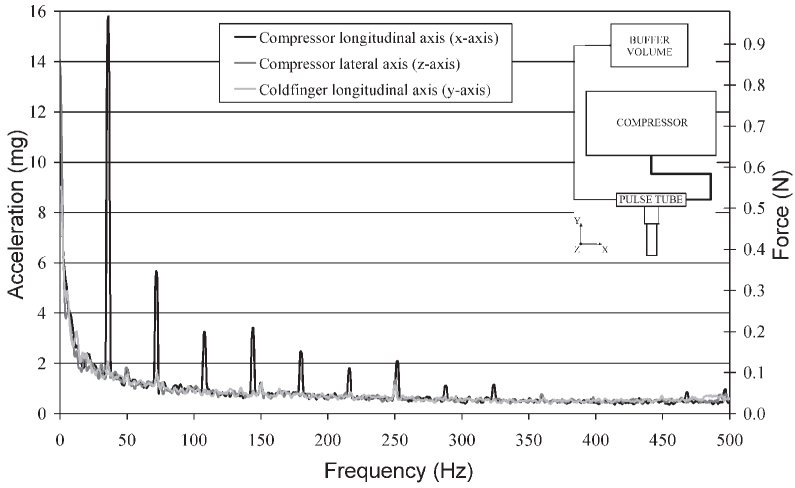

Figure 6. Vibration output data of SF100 Pulse-Tube cooler

QUALIFICATION PROCEDURES

Lifetime Qualification

There are several failure mechanisms which can lead to a failure. AIM has extensive experience in linear cryocoolers. Field data from more than 30,000 cryocoolers provide the statistical basis. Table 3 shows the failure probability of the AIM Flexure Bearing pulse-tube cryocoolers for space applications. The values are based on Ross[1] and field data.

Organic Contamination

Organic contamination is a lifetime limiting factor for cryocoolers. This process is strongly time dependent but because of the long lifetime a real time testing is not deemed as feasible. Instead, an accelerated evaluation scheme had been developed. This procedure foresees two independent test series described in Table 4.

Table 3. Failure mechanisms of space cryocoolers

Failure mechanism	failure probability SL-Cooler	failure probability SF-Cooler	Note
Excessive internal cooler conatamination	0,5%	0,07%	Contamination potential of compressor decreased to 3% of SL100, no contamination potential inside of Pulse-Tube coldfinger / Lifetime increased from 10.000 to 50.000 h
Compressor piston blowby due to seal wear	0,1%	0%	No Wear Out due to flexure Bearing and computer based alignment of piston
Compressor flexure spring breakage from fatigue	-	0,1%	Value from "Cooler Reliability and Redundancy Considerations for long-life Space Missions". Piston stroke during operation is less then 25% of Fatigue limit.
Cryocooler electronics failure	1%	1%	Values from field. (50% depending on use of tantalum capacitors, fixed by corrective action)
Gas leckage	0,05%	0,04%	Values from field, C-Seal Leckage not relevant, Lifetime increased from 10.000 to 50.000 h.
Feedthrough leak	0,05%	0%	Colis are outside of helium vesselt
Compressor piston position sensor failure	0%	0%	No Sensor
Compressor piston alignment failure (binding)	0%	0%	Alignment failure only in case of spring breakage
Compressor motor wiring isolation breakdown	<0.005%	<0.005%	Never seen in field (>30.000 cooler)
Expanded balancer position sensor failure	0%	0%	No Sensor
Expander structural failure (e.g. at launch)	0.20%	0.20%	From "Cooler Reliability and Redundancy Considerations for long-life Space Missions"
Expander blowby due to long-term wear	0,5%	0%	No wear due to no moving parts
Expander motor wiring isolation breakdown	0%	0%	Passive Expander
Expander spindle aAlignment failure (binding)	0%	0%	Not relevant for Pulse-Tube

After finishing 5,000 hours of real time testing, a set of qualification models is to be evaluated with respect to contamination by means of gas chromatography. Knowing the average contamination after 5,000 hrs. A trend can be establish which can be linearly extrapolated to the specified lifetime as is 60,000 hrs for typical space profiles. This approach implies a linear contaminant increase with time [Figure 7, dashed line] which is highly conservative as performance degradation typically declines over time. The linear extrapolation results in a worst case value of gas contamination [Figure 7, notation 5] to be withstood by the second test series carried out under deliberate contamination.

The second test series contrasts the extrapolated worst case contamination [Figure 7, dot] with a contamination level causing a series of identical qualification coolers to fail [Figure 8, filled dot].

The test units will be operated under identical conditions except that they are continuously and controlled fed with contaminant material, naturally existing within the system. This approach allows the slow contaminant diffusion processes to be replicated within a short time frame causing the test units to degrade in an accelerated way. Eventually the qualification models reach specification limit [Figure 8, notation 6] and are to be examined by gas chromatography giving the respective, quantitative contamination [Figure 8, notation 7].

Assuming that cryocooler performance, widely expressed by rated input power, linearly increases with system contamination [Figure 8, dashed line] one can insert the extrapolated worst case contamination from previous step, i.e. [Figure 8, blank dot] providing the derivation of the corresponding power consumption [Figure 8, X]. If the examined quantity of contaminants for the accelerated test specimens is of higher order than the linearly predicted worst case contamination, i.e. positive performance margin [Figure 8, Index 9], the expected cooler lifetime is proven.

Table 4. Accelerated lifetime qualification scheme

Procedure	Remark
1a) 5000 hrs real time testing	Establishment of trend for performance degradation due to contaminant precipitation at coldtip
1b) Extrapolation	Linear extrapolation of performance to specified lifetime
2a) Accelerated testing until failure	Controlled and deliberate contamination of test specimen to provoke spec limit
2b) Comparison and Evaluation	Merging of extrapolated real time(1b) and accelerated test(2a) enables verification of lifetime with respect to contamination

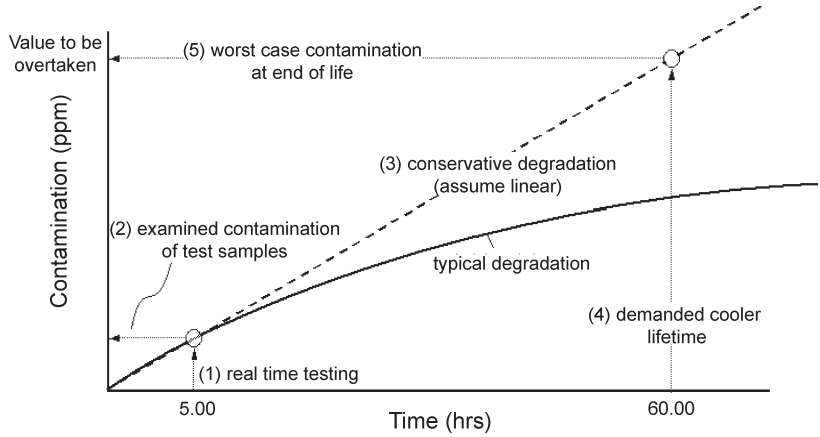

Figure 7. Extrapolation of degradation established by real time testing

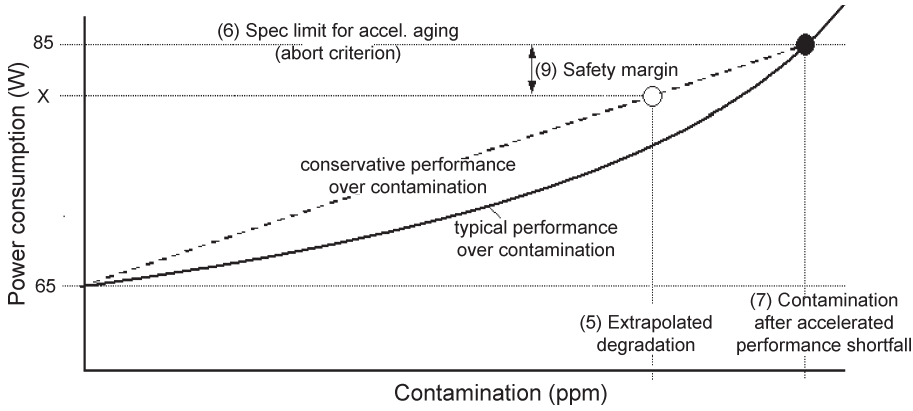

Figure 8. Deliberate contamination of qualification models

Wear out

Due to the Flexure Bearing design, compressor related wear out is well controlled and thus does not limit the lifetime of the cooler. Examinations of endurance test units have shown that neither compressor nor Pulse-Tube exhibited any sign of wear.

Fatigue

For highest compactness of the compressor a welding joint for the Flexure Bearing spring was developed. Flexure bearing springs and supporting weld seams are critical components and have been qualified by cyclic testing, resulting in a Woehler diagram given in Figure 9. For each stroke 20 springs were tested. During the tests, the actual stroke was monitored with a laser stroke sensor. The results confirm more than 35% margin (in tension) to the endurance level at max geometrical stroke. For nominal stroke at full input power (=65% of max stroke) the safety factor is about 2.1 and thus sufficient. Additionally, mentioned displacements have been performed at varying ambient conditions ranging from 23 to –54°C to include effects of brittleness.

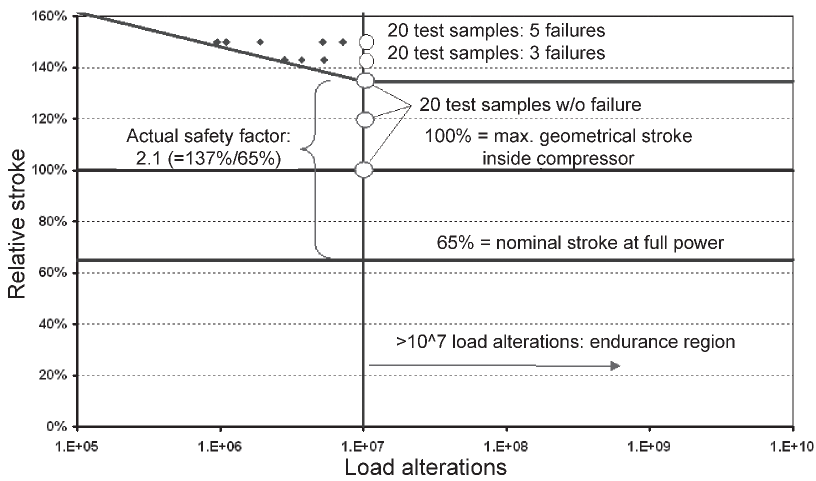

Figure 9. Woehler curve for Flexure Spring assembly of AIM SF100 tactical cryocooler

CONCLUSION

AIM has developed space cryocoolers as part of the IDCA's for EnMAP and KOMPSAT-3A satellite mission. Based on tactical cryocoolers from serial production, AIM Flexure Bearing compressors in combination with a pulse-tube coldfinger have been adapted for space applications. The internal designs of the cooler's components (compressor, Pulse-Tube coldfinger and buffer volume) have not been changed. The mechanical and thermal interfaces were adapted to the satellite structure to meet the mission's requirements.

The prequalification at the cooler level demonstrate that the coolers will fulfill the specification of EnMap and KOMPSAT. At the moment the qualification model for the KOMPSAT satellite will be assembled. The qualification will be performed on IDCA level starting in the near future.

A performance improvement program will decrease the power consumption of the cooler for future space applications. In addition, the development of a digital cooler control electronics for the tactical cooler is in progress. An enhanced space version of this electronics may provide vibration control.

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