Hodge-DeRham theory with degenerating coefficients

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Abstract

Let \( \mathcal{L} \) be a local system on the complement \( X^* \) of a normal crossing divisor (NCD) \( Y \) in a smooth analytic variety \( X \) and let \( j : X^* = X - Y \to X \) denotes the open embedding. The purpose of this paper is to describe a weight filtration \( W \) on the direct image \( j_* \mathcal{L} \) and in case a morphism \( f : X \to D \) to a complex disc is given with \( Y = f^{-1}(0) \), the weight filtration on the complex of nearby cocycles \( \Psi_f(\mathcal{L}) \) on \( Y \). A comparison theorem shows that the filtration coincides with the weight defined by the logarithm of the monodromy and provides the link with various results on the subject.

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1§. Introduction

We consider a local system \( \mathcal{L} \) on the complement \( X^* \) of a normal crossing divisor (NCD) \( Y \) in a smooth analytic variety \( X \) and let \( j : X^* = X - Y \to X \) denotes the open embedding. The purpose of this paper is to describe a weight filtration \( W \) on the direct image \( j_* \mathcal{L} \) in the category of perverse sheaves and in case a morphism \( f : X \to D \) to a complex disc is given with \( Y = f^{-1}(0) \), the weight filtration on the complex of nearby cocycles \( \Psi_f(\mathcal{L}) \) on \( Y \).

This subject started with Deligne’s paper [8] when \( \mathcal{L} = C \) (Steenbrink treated the complex of nearby cycles in [32]), then developed extensively again after the discovery of the theory of intersection cohomology [17] perverse sheaves [2] and the purity theorem [2], [5], [24]. The theory of differential modules introduced by Kashiwara proved to be fundamental in the understanding of the problem as it appeared in the work of Malgrange [28], Kashiwara [24]-[26] and later M. Saito [29],[30]. It is interesting to treat the problem by the original logarithmic methods as proposed in the note [14], in order to obtain topological interpretation of these results in the direction of [27](for another direction [15]). Let me explain now the problems encountered in the construction of a mixed Hodge structure (MHS) for \( X \) proper on the cohomology \( H^*(X - Y, \mathcal{L}) \).

Hypothesis 1. Let \( \mathcal{L} \) be a local system defined over \( \mathbb{Q} \), on the complement of the normal crossing divisor (NCD) \( Y \) in a smooth analytic variety \( X \), \( (\mathcal{L}_X, \nabla) \) the canonical extension of \( \mathcal{L}^\mathbb{C} = \mathcal{L} \otimes \mathbb{C} \) [6] with a meromorphic connection \( \nabla \) having a regular singularity along \( Y \) in \( X \) and the associated DeRham logarithmic complex \( \Omega_X^*(\text{Log}Y) \otimes \mathcal{L}_X \) defined by \( \nabla \) (in the text we write \( L \) and \( \mathcal{L} \) for the rational as well complex vector spaces).

In order to construct a weight filtration \( W \) by subcomplexes of \( \Omega_X^*(\text{Log}Y) \otimes \mathcal{L}_X \) we need a precise description of the correspondence with the local system \( \mathcal{L} \). For all subset \( M \) of \( I \), let \( Y_M = \cap_{i \in M} Y_i \) and \( Y_M^* = Y_M - \cup_{i \notin M} Y_i \), \( j_M : Y_M^* \to Y_M \) the locally closed embeddings, then \( Y_M - Y_M^* \) is a NCD in \( Y_M \) and the open subsets \( Y_M^* \) of \( Y_M \) form with \( X^* \) a natural stratification of \( X \) (we suppose the NCD \( Y = \cup_{i \in I} Y_i \) equal to the union of irreducible and smooth components \( Y_i \) for \( i \) in \( I \)). All extensions of \( \mathcal{L} \) that we will introduce will be constructible with respect to this stratification and even perverse. In fact we will need a combinatorial model of \( \Omega_X^*(\text{Log}Y) \otimes \mathcal{L}_X \) for the description of the weight.

If we consider a point \( y \in Y_M^* \) and a variation of Hodge structures on \( \mathcal{L} \) of weight \( m \), locally defined by a nilpotent orbit \( L \) and a set of nilpotent endomorphisms \( N_i, i \in M \), the
nilpotent orbit theorem [4], [24] states that it degenerates along $Y^*_M$ into a variation of $MHS$ with weight filtration $W^M = W(\Sigma_{i \in M} N_i)$ shifted by $m$, however this result doesn’t lead directly to a structure of mixed Hodge complex since what happens at the intersection of $Y_M$ and $Y_K$ for two subsets $M$ and $K$ of $I$ couldn’t be explained until the discovery of perverse sheaves. The $MHS$ we are looking for cannot be obtained from Hodge complexes defined by smooth and proper varieties, so it was only after the purity theorem [2], [5], [24] and the work on perverse sheaves [2], that the weight filtration $W(N)$ on $\Psi_f(L)$ has been defined by the logarithm of the monodromy $N$ in the abelian category of perverse sheaves (object not trivial to compute). In characteristic zero this has been successfully related to the theory of differential modules [29]. In this work we study the construction of the weight filtration given in the note [14] with new general proofs of the purity and decomposition statements there. The key result that enables us to simplify most of the proofs is the following decomposition (see §2): 

$$Gr^r W^M L = \oplus_{\Sigma_i m_i = r} Gr^W_{m_n} \cdots Gr^W_{m_1} L$$

and in fact the intersection complexes defined by the local systems on $Y^*_M$ with fiber:

$$\oplus_{\Sigma_i m_i = r - |M|, m_i \geq 0} Gr^W_{m_n} \cdots Gr^W_{m_1} (L/(N_1 L + \cdots + N_n L))$$

will be the Hodge components of the decomposition of the graded part of the weight filtrations (of the primitive parts in the case of nearby cocycles). This main result in the open case, its extension to the case of nearby cocycles and its comparison with Kashiwara and Saito’s results form the contents of the article in the second and third sections. We hope that this comparison will be helpful to the reader who doesn’t want to go immediately through the whole subject of differential modules.

One important improvement in the new purity theory with respect to the theory of mixed Hodge complexes in [8], [9] is the fact that the objects can be defined locally: these objects are the intermediate extensions of $VHS$ on $Y^*_M$ for some $M \subset I$ since such extension is defined on $Y_M$ even if it is not proper which makes such objects very pleasant to use especially in the $\Psi_f$ case. We adopt here the convention to use the terminology of perverse sheaves up to a shift in degrees, although it is very important to give explicitly this shift when needed in a proof.

Let us review the contents: the definition of the weight is in (§1, II, 2) formula (14); the main results are in §2, namely the key lemma for the decomposition at the level of the weights (I, 1), the local purity (I, 3), the local decomposition (II) and the global decomposition (III). In §3, the weight of the nilpotent action on $\Psi_f$ is in (I), the local decomposition in (I, 1), the global decomposition in (II, 2), the comparison in (II) and in an example we apply this theory to remove the base change in Steenbrink’s work. In the last part we just state the results for good $VMHS$ as there is no new difficulties in the proofs. Finally we suggest strongly to the reader to follow the proofs on an example, sometimes on the surface case as in (II.1.5), or for $X$ a line and $Y = 0$ a point, then the fiber at 0 of $\Psi_f L$ is a complex $L \to N$ where $(L, N)$ is the nilpotent orbit of weight $m$ defined at $y$ and the weight on the complex is $W[m]$ defined by $W[m]_{r+m} = W_r = (W_{r+1} L \to W_{r-1} L)$. This example will be again useful for $\Psi_f L$ in §3.

I. Preliminaries on perverse extensions and nilpotent orbits

In the neighbourhood of a point $y$ in $Y$, we can suppose $X \simeq D^{n+k}$ and $X^* \simeq (D^*)^n \times D^k$ where $D$ is a complex disc, denoted with a star when the origin is deleted. The fundamental
group $\Pi_1(X^*)$ is a free abelian group generated by $n$ elements representing classes of closed paths around the origin, one for each $D^*$ in the various axis with one dimensional coordinate $z_i$ (the hypersurface $Y_i$ is defined by the equation $z_i = 0$). Then the local system $\mathcal{L}$ corresponds to a representation of $\Pi_1(X^*)$ in a vector space $L$, i.e. the action of commuting automorphisms $T_i$ for $i \in [1,n]$ indexed by the local components $Y_i$ of $Y$ and called monodromy action around $Y_i$. The automorphisms $T_i$ decomposes as a product of commuting automorphisms, semi-simple and unipotent $T_i = T_i^s T_i^u$. When $L$ is a $\mathbb{C}$-vector space, $T_i^a$ can be represented by the diagonal matrix of its eigenvalues. If we consider sequences of eigenvalues $a_i$ for each $T_i$ we have the spectral decomposition of $L$

\begin{equation}
L = \oplus_{a_i} L^{a_i} \quad , \quad L^{a_i} = \cap_{i \in [1,n]} (\cup_{j>0} \ker (T_i - a_i I)^j)
\end{equation}

where the direct sum is over all families $(a_i) \in \mathbb{C}^n$. The logarithm of $T_i$ is defined as the sum

\begin{equation}
\text{Log}T_i = -2\pi i (D_i + N_i) = \text{Log} T_i^s + \text{Log} T_i^u
\end{equation}

where $-2\pi i D_i = \text{Log} T_i^a$ is the diagonal matrix formed by $\text{Log} a_i$ for all eigenvalues $a_i$ of $T_i^a$ and for a fixed determination of $\text{Log}$ on $\mathbb{C}^*$, while $-2\pi i N_i = \text{Log} T_i^u$ is defined by the polynomial function $-2\pi i N_i = \sum_{k \geq 1} (1/k) (I - T_i^u)^k$ in the nilpotent $(I - T_i^u)$ so that the sum is finite.

Now we describe various local extensions of $\mathcal{L}$.

### 1.1 The (higher) direct image $j_* \mathcal{L}$, local and global description

The complex $j_* \mathcal{L}$ is perverse and its fiber at the origin in $D^{n+k}$ is quasi-isomorphic to a Koszul complex as follows. We associate to $(L, (D_i + N_i), i \in [1,n])$ a strict simplicial vector space such that for all sequence $(i_j) = (i_1 < \cdots < i_p)$

\[ L(i_j) = L, \quad D_{i_j} + N_{i_j}; L(i_j, i_{j+1}) \to L(i_j). \]

The associated simple complex is the Koszul complex or the exterior algebra defined by $(L, D_i + N_i)$ denoted by $\Omega(L, D_i, N_i,j) = s(L(J), D_i + N_i, J \subset [1,n])$ where $J$ is identified with the strictly increasing sequence of its elements and where $L(J) = L$. It can be checked that its cohomology is the same as $\Omega(L, Id - T_i)$, the Koszul complex defined by $(L, Id - T_i), i \in [1,n]$.

When we fix a family $\alpha_j \in [0,1]$ for $j \in [1,n]$ such that $e(\alpha_j) = e^{-2\pi i \alpha_j}$ is an eigenvalue for $D_j$, we have

\begin{equation}
\Omega(L, D_i, N_i) = s(L(J), D_i, N_i, J \subset [1,n], \oplus_{\alpha_j} \Omega(L^{e(\alpha_j)}, \alpha_j Id + N_i).
\end{equation}

In particular each sub-complex is acyclic when $\alpha_j$ is not zero since then $\alpha_j Id + N_j$ is an isomorphism. This local setting compares to the global case via Grothendieck and Deligne DeRham cohomology results. Let $y \in Y_M^*$, then

\begin{equation}
(j_* \mathcal{L})_y \simeq \Omega^*_X(\text{Log} Y) \otimes \mathcal{L}_X)_y \simeq \Omega(L, D_j + N_j, j \in M)
\end{equation}

When we start with a $\mathbb{Q}$ local system, $\mathcal{L}_X$ is equal to the canonical extension with residue $\alpha_j \in [0,1]\cap \mathbb{Q}$ such that $a_j = e^{-2\pi i \alpha_j}$. An element $v$ of $L^{e(\alpha_j)} = L^{(\alpha_j), J \subset M}$, corresponds to the section $\tilde{v} \otimes \frac{dz_j}{z_j^{\alpha_j}}$ of $(\mathcal{L}_X \otimes \frac{dz_j}{z_j^{\alpha_j}})_y$, where $\frac{dz_j}{z_j^{\alpha_j}} = \Lambda_{\alpha_j} J \frac{dz_j}{z_j}$ by the formula

\begin{equation}
\tilde{v}(z) = \left(\exp(\Sigma_{j \in J} \text{Log} z_j (\alpha_j + N_j))\right) v = \Pi_{j \in J} z_j^{\alpha_j} \exp(\Sigma_{j \in J} \text{Log} z_j N_j). v
\end{equation}
a basis of $L$ is sent on a basis of $(L_X)_y$, the endomorphisms $D_j + N_j$ defines corresponding endomorphisms denoted by the same symbols on the image sections $\tilde{v}$ and we have

$$\nabla \tilde{v} = \sum_{j \in J} (\alpha_j + N_j) \tilde{v} \otimes \frac{dz_j}{z_j}$$

This description of $(j_*\mathcal{L})_y$ is the model for the description of the next various perverse sheaves.

1.2 The intermediate extension $j_*\mathcal{L}$  Let $(D + N)_J = \Pi_{j \in J} (D_j + N_j)$ denotes a composition of endomorphisms of $L$, we consider the strict simplicial sub-complex of the DeRham logarithmic complex (2.4) defined by $Im(D + N)_J$ in $L(J) = L$. The associated simple complex will be denoted by

$$IC(L): = s((D + N)_J L, (D + N)_J)_{J \subset [1,n]}$$

The intermediate extension $j_*\mathcal{L}$ of $\mathcal{L}$ is defined by an explicit formula in terms of the stratification \[24, \S3\]. Locally its fiber at a point $y \in Y^*_M$ is given in terms of the above complex

$$j_*\mathcal{L}|_y \cong IC(L) \cong s((D + N)_J L, (D + N)_J)_{J \subset M}$$

The corresponding global DeRham description is given as a sub-complex $IC(X, \mathcal{L})$ of $\Omega^*_X (Log Y) \otimes \mathcal{L}_X$. The residue of the connection $\nabla$ along each $Y_j$ defines an endomorphism $(D_j + N_j)$ on the restriction $\mathcal{L}_{Y_j}$ of $\mathcal{L}_X$, then in terms of a set of $n$ coordinates $y_i, i \in [1,n]$ defining $Y_M$ on an open set $U_y$ containing $y \in Y^*_M$ where we identify $M$ with $[1,n] = M ( n = |M| )$ and a section $f = \sum_{J \subset M, J \cap M = \emptyset} f_J y_J(\frac{dy_J}{y_J}) \wedge dy_J$, we have

$$f \in IC(U_y, \mathcal{L}) \Leftrightarrow \forall J \subset M, f_{J,J'}/Y_J \in (D_J + N_J)(\mathcal{L}_{Y_J})$$

A global definition of $IC(X, \mathcal{L})$, using notations of \[26\], is given as follows. Consider $M \subset I$ and for all $J \subset M$ the families of sub-bundles $(D_J + N_J)(\mathcal{L}_{Y_J})$ of $\mathcal{L}_{Y_J}$, then define for each $M$ the sub-module $\mathcal{T}(M)$ of $\mathcal{L}_X$ consisting of sections $v$ satisfying:

$$v \in \mathcal{T}(M) \Leftrightarrow \forall J \subset I, v/Y_J \in (D_{M \cap J} + N_{M \cap J})(\mathcal{L}_{Y_J})$$

This submodule is well defined since we have, for $J \subset K$, the inclusion $(D_J + N_J)(\mathcal{L}_{Y_J}) \subset (D_K + N_K)(\mathcal{L}_{Y_K})$. Let $\Omega^*_M$ be the $\Omega^*_X$ sub-exterior algebra of $\Omega^*_X (Log Y)$ generated by $\Omega^*_X (Log Y)$ for $i \in M$. Then we can define

$$IC(X, \mathcal{L}) = \sum_{M \subset I} \Omega^*_M \otimes \mathcal{T}(M) \subset \Omega^*_X (Log Y) \otimes \mathcal{L}_X.$$

In terms of the decomposition (3), since the endomorphism $(\alpha_D Id + N_J)$ is an isomorphism on $\mathcal{L}^{(\alpha_D)}_J$ whenever $\alpha_D \neq 0$, we introduce for each set $\alpha$, the subset $I(\alpha)$ of $[1,n]$ such that $j \in I(\alpha)$ iff $\alpha_D = 0$, then for each $J \subset [1,n]$, $(D + N)_J L^{(\alpha)} = N_{J \cap I(\alpha)} L^{(\alpha)}$ where $N_{J \cap I(\alpha)} = \Pi_{j \in J \cap I(\alpha)} N_j$ (the identity if $J \cap I(\alpha)$ is empty). Then locally the fiber of $j_*\mathcal{L}$ at a point $y \in Y^*_M$ is

$$j_*\mathcal{L}|_y \cong IC(L) \cong \oplus_{\alpha_D} s(N_{J \cap I(\alpha)} L^{(\alpha_D)})_{J \subset M}$$

**Remark:** The fiber of the complex $(\Omega^*_X (Log Y) \otimes \mathcal{L}^{(\alpha_D)}_X)_y$ is acyclic if there exists an index $j \in M$ such that $\alpha_D \neq 0$. 

4
1.3 Hodge filtration, Nilpotent orbits and Purity

Hypothesis 2: Variation of Hodge structures (VHS). Consider the flat bundle \((L_X, \nabla)\) in the previous hypothesis and suppose now that \(L_X^*\) underlies a VHS that is a polarised filtration by subbundles \(F\) of weight \(m\) satisfying Griffith’s conditions [19].

The nilpotent orbit theorem [19], [4], [24], [25], states that \(F\) extends to a filtration by subbundles \(F\) of \(L_X\) such that the restrictions to open intersections \(Y^*_M\) of components of \(Y\) underly a variation of mixed Hodge structures \(VMHS\) where the weight filtration is defined by the nilpotent endomorphism \(N_M\) defined by the connection.

Local version.

Near a point \(y \in Y^*_M\) with \(|M| = n\) a neighbourhood of \(y\) in the fiber of the normal bundle looks like a disc \(D^n\) and the above hypothesis reduces to

Local Hypothesis 2: Nilpotent orbits [4]. Let

\[
(12) \quad (L, N_i, F, P, m, i \in M = [1, n])
\]

be defined by the above hypothesis, that is a \(\mathbb{Q}\) vector space \(L\) with endomorphisms \(N_i\) viewed as defined by the horizontal (zero) sections of the connection on \((D^*)^n\), a Hodge structure \(F\) on \(L^C = L \otimes_{\mathbb{Q}} \mathbb{C}\) viewed as the fiber of the vector bundle \(L_X\) at \(y\) (here \(y = 0\)), a natural integer \(m\) the weight and the polarisation \(P\).

The main theorem [4] states that for all \(N = \Sigma_{i \in M} \lambda_i N_i\) with \(\lambda_i > 0\) in \(\mathbf{R}\) the filtration \(W(N)\) (with center 0) is independant of \(N\) when \(\lambda_i\) vary and \(W(N)[m]\) is the weight filtration of a polarised \(MHS\) called the limit \(MHS\) of weight \(m\) (\(L, F, W(N)[m]\)).

Remark: \(W(N)[m]\) is \(W(N)\) with indices shifted by \(m\) to the right: \((W(N)[m])_z = W_{r-m}(N)\), the convention being a shift to left for a decreasing filtration and to right for an increasing filtration.

We say that \(W(N)\) defines a \(MHS\) of weight \(m\) on \(L\). It is very important to notice that the same orbit underlies other different orbits depending on the intersection of components of \(Y\) (here the intersection of the axis of \(D^n\)) where the point \(z\) near \(y\) is considered, in particular \(F_z \neq F_y\). In this case when we restrict the orbit to \(J \subset M\), we should write

\[
(L, N_i, F(J), P, m, i \in J \subset M)
\]

Finally we will need the following result [4 p 505]: Let \(I, J \subset M\) and let \(N_J = \Sigma_{i \in J} N_i\) then \(W(N_I)\) is the weight filtration of \(N_J\) relative to \(W(N_I)\)

\[
\forall j, i \geq 0, N_j^i : Gr^W_{i+j}(N_{I \cup J}) Gr^W_{j}(N_I) \simeq Gr^W_{j-i}(N_{I \cup J}) Gr^W_{j}(N_I).
\]

II. The weight filtration on the logarithmic complex

Now we want to give the construction of the weight filtration given in [14] and based on a general formula of the intersection complex given by Kashiwara and Kawai [26]. Earlier work in the surface case using ad hoc methods showed that the purity and the decomposition theorems could be obtained out of similar considerations.

To this purpose we introduce a category \(S(I) = S\) attached to a set \(I\). We start with a local study, that is to say with the hypothesis of a polarised nilpotent orbit and we describe the weight filtration \(W\) on the DeRham complex \(\Omega(L, N)\). In fact the filtration \(W\) is defined on
a quasi-isomorphic complex and may appear unrealistic at first sight, however the features of
the purity theory will appear relatively quickly. First we ask the reader to take some time to
get acquainted with the new category $S(I)$ serving as indices for the new complex. The lowest
weight is given by the intermediate extension of $L$ or $IC(L)$, then for the higher weights we
need to introduce the complexes $C^{KM}_rF$ for $K \subset M \subset I$ which describe the geometry of
the decomposition theorem ($\S 2$, II) and the purity theory ($\S 2$, I.3) where the proof reflects deep
relations between the weight filtrations of the various $N_i$.

1.4 Complexes with indices in the category $S(I)$. We introduce a category $S(I) = S$
attached to a set $I$, whose objects consist of sequences of increasing subsets of $I$ of the following
form:

$$(s.) = (I = s_1 \supseteq s_2 \ldots \supseteq s_p \neq \emptyset), \ (p > 0)$$

Subtracting a subset $s_i$ from a sequence $s$ defines a morphism $\delta_i(s.) : (s. - s_i) \to s.$ and
more generally $Hom(s.'., s.)$ is equal to one element iff $(s.' \leq (s.)$. We write $s. \in S$ and define
its degree $| s. |$ as the number of subsets $s_i$ in $s.$ or length of the sequence.

Correspondence with an open simplex. If $I = \{1, \ldots, n\}$ is finite, $S(I)$ can be realised as
a barycentric subdivision of a simplex of dimension $n - 1$, a subset $K$ corresponding to the
barycenter of the vertices in $K$ and a sequence of subsets to the simplex defined by the vertices
associated to the subsets. Since all sequences contain $I$, all corresponding simplices must have
the barycenter as vertex, that is: $S(I)$ define a simplicial object computing the $n^{th}$ homology
-group with closed support of the open simplex. This remark leads us to the next definition.

Simplicial complex defined by complexes with indices in $S(I)$. An algebraic variety over a
fixed variety $X$ with indices in $S$ is a covariant functor $\Pi : X_s \to X$ for $s. \in S$. An abelian sheaf
(resp. complex of abelian sheaves) $F$ is a family of abelian sheaves (resp. complex of abelian
sheaves) $F_s.$ over $X_s.$ and functorial morphisms $F_{s.} \to F_{s.'}$ for $(s.' \leq (s.)$.

The direct image of an abelian sheaf (resp. complex of sheaves) denoted $\Pi_*F$ or $s(F_{s.}, s. \in S$
is the simple complex(resp.simple complex associated to a double complex) on $X$:

$$\Pi_*F := \oplus_{s. \in S} (\Pi_*F_{s.})[| s. | - | I |], \ d = \Sigma_{i \in [1, |s. |]}(-1)^i F(\delta_i(s.)).$$

The variety $X$ defines the constant variety $X_s.$ = $X$. The constant sheaf $\mathbb{Z}$ lifts to a sheaf on
$X_s.$ such that the diagonal morphism $: Z_X \to \oplus_{|i| = |I|} Z_{X_{s_i}}$ (that is : $n \in \mathbb{Z} \to \ldots, n_{s_i}, \ldots \in
\oplus_{|i| = |I|} \mathbb{Z}$ defines a quasi-isomorphism $Z_X \cong \Pi_*\Pi^*(Z_X)$. This is true since $S(I)$ is isomorphic
to the category defined by the barycentric subdivision of an open simplex of dimension $| I | - 1$.

1.5 Local definition of the weight filtration.
Our hypothesis here consists again of the nilpotent orbit $(L, (N_i)_{i \in M}, F, m, P)$ of weight $m$
and polarisation $P$ and the corresponding filtrations $(W^j)_{J \subset M}$.
We will use the category $S(M)$ attached to $M$ whose objects consist of sequences of decreasing
subsets of $M$ of the form $(s.) = (M = s_1 \supseteq s_2 \ldots \supseteq s_p \neq \emptyset), \ (p > 0)$.
In this construction we will need double complexes, more precisely complexes of the previously
defined exterior complexes. They correspond to objects with indices in the category $M^+ \times S(M)$
where the objects of $M^+$ are the subsets $J \subset M$ including the empty set. Geometrically $M$
corresponds to a normal section to $Y^*_M$ in $X$ and $J \to \wedge_{i \in J} dz_i$ in the exterior DeRham complex


written as \( s(L_J)_{J \subseteq M} \) on the normal section to \( Y^*_M \) and the decomposition \( M^+ \cong (M - K)^+ \times K^+ \) corresponds to the isomorphism \( C^M \cong C^M(K^+ \times K) \).

**Notations.** For each \( s \in S(M) \), \( J \subseteq M \) and integer \( r \) we define \( a_{s_\lambda}(J, r) = |s_\lambda| - 2 \) \( s_\lambda \cap J \mid + r \)

\[ F_r(J, s.) = \bigcap_{s_\lambda \in s.} W^{s_\lambda}_{a_{s_\lambda}(J, r)} L, \quad F^r(J, s.) = F^r-|J|/L, \quad (a_{s_\lambda}(J, r) = |s_\lambda| - 2 \) \( s_\lambda \cap J \mid + r \)

where \( W^{s_\lambda} \) is centered at 0, then we define on the DeRham complex \( \Omega(L, N.) \), the filtrations by sub-complexes \( W(s.) \) (weight) and \( F(s.) \) (Hodge) as

\[ W_r(s.) = s(W_r(J, s.))_{J \subseteq M}, \quad F^r(s.) = s(F^r(J, s.))_{J \subseteq M} \]

and finally

**Definition:** The weight (centered at zero) and Hodge filtrations on the combinatorial DeRham complex \( \Omega^*L = s(\Omega(L, N.))_{s \in S(M)} \) are defined by “summing” over \( s \) as:

\[ F_r^* = s(F_r(s.))_{s \in S(M)} \subseteq s(L(s.))_{s \in S(M)}, \quad W_r^*(\Omega^*L) = s(W_r(s.))_{s \in S(M)} \subseteq s(L(s.))_{s \in S(M)} \]

**Exercise in dimension 2.** Let \( W^{1,2} = W(N_1 + N_2), W^1 = W(N_1) \) and \( W^2 = W(N_2) \), the weight \( W_r \) is a double complex where the first line is the direct sum for \( \{1, 2\} \nsubseteq \emptyset \) and \( \{1, 2\} \nsubseteq \emptyset \) of:

\[ W^{1,2}_{r+2} \cap W^1_{r+2} \xrightarrow{(N_1, N_2)} W^{1,2}_{r+2} \cap W^1_{r+2} \cap W^1_{r+2} \cap W^1_{r+2} \xrightarrow{(N_2, N_1)} W^{1,2}_{r+2} \cap W^2_{r+2} \]

and

\[ W^{1,2}_{r+2} \cap W^2_{r+2} \xrightarrow{(N_1, N_2)} W^{1,2}_{r+2} \cap W^2_{r+2} \cap W^2_{r+2} \xrightarrow{(N_2, N_1)} W^{1,2}_{r+2} \cap W^2_{r+2} \]

The second line for \( \{1, 2\} \) is

\[ W^{1,2}_{r+2} \xrightarrow{(N_1, N_2)} W^{1,2}_{r+2} \xrightarrow{(N_2, N_1)} W^{1,2}_{r+2} \]

which reduces to the formula in [26] for \( r = m \).

### 1.6 The Complexes \( C_r^{K M}L \) and \( C_r^KL \)

To study the graded part of the weight, we need to introduce the following subcategories:

For each subset \( K \subseteq M \), let \( S_K(M) = \{ s \in S(M) : K \subseteq s \} \) and consider the isomorphism of categories:

\[ S(K) \times S(M - K) \cong S_K(M), \quad (s, s') \rightarrow (K \cup s', s) \]

We consider the vector space with indices \((J, s.) \in M^+ \times S_KM\), and its associated complex

\[ C_r(J, s.)L := \bigcap_{K \neq s_\lambda \in s.} W^{s_\lambda}_{a_{s_\lambda}(J, r - 1)} G^{W_K}_{a_{s_\lambda}(J, r)} L, \quad C_r(s.)L := s(C_r(J, s.))_{J \subseteq M^+} \]

we define as well \( C_r(J, s.)N_J L \) and \( C_r(J, s.)(L/|N_J|) \) by replacing \( L \) with \( N_J L \) and \( L/|N_J| \), then \( C_r(s.)ICL := s(C_r(J, s.))_{J \subseteq M^+} \) and \( C_r(s.)QL := s(C_r(J, s.))_{J \subseteq M^+} \)

**Definition:** For \( K \subseteq M \) the complex \( C_r^{KM}L \) is defined as

\[ C_r^{KM}L := s(C_r(s.)L)_{s \in S_K(M)}, \quad C_r^{KM}ICL := s(C_r(s.)ICL)_{s \in S_K(M)}, \quad C_r^{KM}QL := s(C_r(s.)QL)_{s \in S_K(M)} \]

**In the case** \( K = M \) we write \( C_r^KL \) (resp. \( C_r^KICL, C_r^KQL \) for \( C_r^{KK}L \) (resp. \( ICL, QL \) instead of \( L \))

\[ C_r^KL := s(C_r(J, s.))_{J, s. \in K^+ \times S(K)} = s(\bigcap_{K \neq s_\lambda \in s.} W^{s_\lambda}_{a_{s_\lambda}(J, r - 1)} G^{W_K}_{a_{s_\lambda}(J, r)} L)_{J, s. \in K^+ \times S(K)} \]
In this section we aim to prove that the filtration is actually the weight of what would be in the proper case a mixed Hodge complex in Deligne’s terminology, that is the induced filtration by \( F \) on the graded parts \( Gr^W \) of \( W \) is a Hodge filtration. For this we need to decompose the complex as a direct sum of intermediate extensions of variations of Hodge structures (which has a meaning locally) whose cohomologies are pure Hodge structures [5] and [24] in the proper case. This is done in the following three subsections. In the first we prove a key lemma that apply to prove the purity of the complex \( C^K_L \). Once this purity result is established, we can easily prove in the second subsection the decomposition theorem after a careful study of the category of indices \( S(I) \). In the third subsection we give the global statements for a filtered combinatorial logarithmic complex. For this we use the above local decomposition to obtain a global decomposition of the graded weight into intermediate extensions of polarised \( VHS \) on the various intersections of components of \( Y \). This last statement uses the formula announced by Kashiwara and Kawai [26] that we prove since we have no reference for its proof.

I. Purity of the cohomology of the complex \( C^K_L \)

In this subsection we introduce the fiber of the variations of Hodge structures needed in the decomposition of \( Gr^W \). The result here is the fundamental step in the general proof. The plan of this subsection is as follows. First we start with a key lemma relating the various relative monodromy weight filtrations (centered at zero) associated to a nilpotent orbit \( L; N_i \) is compatible with \( W(N_j) \) for \( i \neq j \) but shift Hodge filtration by \(-1\), hence it is not clear whether it is strict, however we need technical results to establish the purity and decomposition properties and this key lemma provides what seems to be the elementary property at the level of a nilpotent orbit that leads to the decomposition. Second we present a set of elementary complexes. Finally we state the purity result on the complexes \( C^K_L \) which behave as a direct sum of elementary complexes.

2.1 Properties of the relative weight filtrations

Given the nilpotent orbit we may consider various filtrations \( W^J = W(\Sigma_{i \in J} N_i) \) for various \( J \subset M \). They are centered at 0, preserved by \( N_i \) for \( i \in M \) and shifted by \(-2\) for \( i \in J; N_i W^J_r \subset N_i W^J_{r-2} \). We will need more subtle relations between these filtrations that we discuss in this subsection.

**Key lemma (Decomposition of the relative weight filtrations):** Let \((L, N_i, i \in [1, n], F)\) be a polarised nilpotent orbit and let \( W^i := W(N_i) \) (all weights centered at 0), then:

i) For each subset \( A = \{i_1, \ldots, i_j\} \subset [1, n] \), of length \( |A| = j \)

\[ Gr^L_r W^A \simeq \bigoplus_{m \in X^A_r} Gr^W_{m_{i_1}}^{W^{i_1}} \cdots Gr^W_{m_{i_j}}^{W^{i_j}} L \]

where \( X^A_r = \{m_\in \mathbb{Z}^j : \Sigma_{i \in A} m_i = r\} \) and if \( A = B \cup C \)

\[ Gr^L_r W^A Gr^L_r W^C \simeq Gr^L_r W^B Gr^L_r W^C \]

ii) Let \( N'_i \) denotes the restriction of \( N_i \) to \( G_{i}^{W_C} \) and \( N'_B = \Sigma_{i \in B} N'_i \), then \( W^B \) induces \( W_b(N'_B) \) on \( Gr^L_r W^C \).

iii) In particular the repeated graded objects in (i) do not depend on the order of the elements in \( A \).
Remark: This result gives relations between various weight filtrations in terms of the elementary ones $W^i := W(N_i)$ and will be extremely useful in the study of the properties of the weight filtration on the higher direct image. For example for $N = N_1 + \cdots + N_n$, there exists a canonical decomposition

$$Gr^W_r(N)L = \oplus_{m \in X_r} Gr^W_m \cdots Gr^W_1 L$$

where $X_r = \{ m \in \mathbb{Z}^n : \Sigma_{i \in [1,n]} m_i = r \}$.

The proof by induction on $n$ is based on the following important result of Kashiwara [25, thm. 3.2.9, p. 1002]:

Let $(L, N, W)$ consists of a vector space endowed with an increasing filtration $W$ preserved by a nilpotent endomorphism $N$ on $L$ and suppose that the relative filtration $M = M(N, W)$ exists, then there exists a canonical decomposition:

$$Gr^M_r L = \oplus_k Gr^M_k Gr^W_k L.$$
that is $W_i W l^A Gr_k W^{(A-i)} L = Gr_i W^A Gr_k W^{(A-i)} L$ if $l - k \leq s$ and $W_i W l^A Gr_k W^{(A-i)} L = 0$ otherwise, or

$$Gr_i W^A Gr_j W L \simeq Gr_i W^A Gr_j W^{W_i} Gr_k W^{(A-i)} L,$$

and for all $l \neq k + k'$, $Gr_i W^A Gr_k W^{W_i} Gr_k W^{(A-i)} L \simeq 0$.

In other words: $W^A$ induces a trivial filtration on $Gr_k W^{W_i} Gr_k W^{(A-i)} L$ of weight $k + k'$ that is

$$Gr_i W^A L \simeq \oplus_k Gr_i W^A Gr_k W^{W_i} L \simeq \oplus_k Gr_i W^A Gr_k W^{W_i} L \simeq \oplus_k Gr_k W^{(A-i)} Gr_k W^W L.$$

Now if we suppose by induction on length of $A$, the decomposition true for $A - i$, we deduce easily the decomposition for $A$ from the above result.

ii) In the proof above we can start with any $i$, since $W$ can be expressed using these filtrations, we deduce that $W^i$, $W$, $W^j$ also commute, for example: $Gr_s W^{W_{i+j}} Gr_s W^{W} Gr_s W^{W_i} \simeq Gr_s W^{W} Gr_s W^{W_i}$ is symmetric in $i, j, r$.

**Corollary:** The morphism $N_i$ induces for all $j$, exact sequences for all integers $r$

$$0 \rightarrow W^j \cap \ker N_j \rightarrow W^j L \rightarrow W^j \cap N_j L \rightarrow 0 \hspace{1cm} \text{and} \hspace{1cm} 0 \rightarrow W^j \cap N_j L \rightarrow W^j L \rightarrow W^j (L/N_j L) \rightarrow 0.$$

Proof: $N_i$ is strict for $W^i$ and $W^{i+j}$ hence we have the above exact sequences for $Gr_s W^{W_{i+j}} Gr_s W^W = Gr_s W^W Gr_s W^{W_j}$.

**2.2 Elementary complexes** The proof of the purity uses the following simplicial vector spaces. For each $J \subset [1, n]$, let

$$K((m_1, \ldots, m_n), J) = \bigcap_{m_{i+j}} \cdots Gr_m W_{m_i - 2} V_{m_j - 2} \cdots Gr_m W_{m_i - 2} V_{m_j - 2} L$$

(resp. $L/N_j L$ and $N_j L$). For all $i \notin J$, the endomorphism $N_i$ induces a morphism denoted also $N_i : K((m_1, \ldots, m_n), J) \rightarrow K((m_1, \ldots, m_n), J \cup i)\{1, n\}$, (resp. for $L/N_j L$ and $N_j L$ instead of $L$), then we consider the following elementary complexes defined as simple associated complexes:

$$K(m_1, \ldots, m_n) : = s(K((m_1, \ldots, m_n), J) L, N_i)_{J \subset [1, n]}$$

(resp. $K(m_1, \ldots, m_n) Q L = : s(K((m_1, \ldots, m_n), J) L/N_j L, N_i)_{J \subset [1, n]}$ and $K(m_1, \ldots, m_n) ICL = : s(K((m_1, \ldots, m_n), J) N_j L, N_i)_{J \subset [1, n]}$).

**Proposition:** i) For any $((m_1, \ldots, m_n) \in \mathbb{Z}^n$ let $J(m.) = \{i \in [1, n] : m_i \geq 1\}$, then the cohomology of an elementary complex $K(m_1, \ldots, m_n) L$ is a subquotient of $K((m_1, \ldots, m_n), J(m.) L)$, hence concentrated in degree $| J(m.) |$. Moreover it vanishes iff there exists at least one $m_i = 1$.

More precisely, if no $m_i = 1$, the cohomology is isomorphic to $K((m_1, \ldots, m_n), J(m.)) [(\cap_{i \notin J(m.)} \ker N_i : L/(\sum_{j \in J(m.)} N_j L) \rightarrow L/(\sum_{j \notin J(m.)} N_j L))]$, moreover this object is symmetric in the operations kernel and cokernel and is isomorphic to $K((m_1, \ldots, m_n), J(m.)) [(\cap_{i \in [m_1, 1]} \ker N_i / (\sum_{j \in J(m.1)} N_j / (\sum_{i \in [m_1, 1]} \ker N_i))]]$.

Thus at each process of taking $Gr_m W_i$ we apply the functor ker if $m_i \notin J(m.)$ and coker if $m_i \in J(m.)$.

**ii)** If there exists $m_i > 0$, then $K(m_1, \ldots, m_n) ICL \simeq 0$, hence $K(m_1, \ldots, m_n) L \simeq K(m_1, \ldots, m_n) Q L$.

**iii)** If all $m_i \leq 0$, then
2.3 Main result

Theorem (Purity). Let $L$ be a polarised nilpotent orbit (local hypothesis 2 (§1, I.3)), then the complexes $C_r^K L$ in (§1, II.3) where we suppose $K = M$ of length $|K| = n$, satisfy the following properties

1) Let $r > 0$ and $T(r) = \{(m_1, \ldots, m_n) \in \mathbb{N}^n : \forall i \in K, m_i \geq 2 \}$ and $\Sigma_{j \in K} m_j = |K| + r$

then the cohomology of the complex $C_r^K L$ is isomorphic to that of the following complex

$$C_r^K L \cong C(T(r)) \cong \oplus_{(m_1, \ldots, m_n) \in T(r)} K(m_1, \ldots, m_n) L$$

In particular its cohomology, concentrated in degree $|K|$, is isomorphic to

$$Gr_{r+|K|}[L/(\Sigma_{j \in K} N_j L)] \cong \oplus_{(m_1, \ldots, m_n) \in T(r)} G_m^{W_n} \cdots \cdots \cdot G_m^{W_{r-2}} [L/(\Sigma_{j \in K} N_j L)]$$

it is a polarised Hodge structure of weight $r + m - |K|$ with the induced filtrations $W^K$ (shifted by $m$) and $F^K$. Moreover, if $r = 0$, the complex $C_r^K L$ is acyclic.

2) Dually, for $r < 0$, let $T'(r) = \{(m_1, \ldots, m_n) \in \mathbb{Z}^n : \forall i \in K, m_i \leq 0, \Sigma_{j \in K} m_j = |K| + r \}$,

then the complex $C_r^K L$ is isomorphic to the following complex

$$C_r^K L \cong C(T'(r))[1 - |K|] \cong \oplus_{(m_1, \ldots, m_n) \in T'(r)} K(m_1, \ldots, m_n) L[1 - |K|]$$

In particular its cohomology, concentrated in degree $|K| - 1$, is isomorphic to

$$Gr_{r+|K|}[\cap_{\in K}(ker N_j : L \to L)] \cong \oplus_{(m_1, \ldots, m_n) \in T'(r)} G_m^{W_n} \cdots \cdots \cdot G_m^{W_{r-2}} [\cap_{\in K}(ker N_j : L \to L)]$$

it is a polarised Hodge structure of weight $r + m + |K|$ with the induced filtrations $W^K$ (shifted by $m$) and $F^K$.

3) The complex $C_r^K L$ is quasi-isomorphic to $C_r^K Q(16)$ for $r \geq 0$ and to the complex $C_r^K ICL$ (16) for $r \leq 0$.

Remark: If $r \in [1, |K| - 1]$, $T(r)$ is empty and $C_r^K L$ is acyclic. If $r \in [-|K| + 1, 0]$, $T'(r)$ is empty and $C_r^K L$ is acyclic. In all cases $C_r^K L$ appears in $Gr^{W \Omega^*(L)}$.

Proof: The important fact used here is the particular decomposition for a nilpotent orbit of the relative filtrations, that is the isomorphism, functorial for the differentials of $C_r^K L$

$$Gr_{(J,s)\in X(J,s)} W_{\alpha(x(J,s-1))}^\alpha L \cong \oplus_{m \in X(J,s)} G_m^{W_n} \cdots \cdots \cdot G_m^{W_{r-2}} [\cap_{\in K}(ker N_j : L \to L)]$$
where for all \((J, s.) \in K^+ \times S(K)\),
\[
X(J, s., r) = \{ m. \in \mathbb{Z}^n : \Sigma_{i \in K} m_i = a_K(J, r) \text{ and } \forall s_\lambda \in s., \Sigma_{i \in s_\lambda} m_i \leq a_\lambda(J, r - 1) \}
\]
In particular, if we define for \(J \in \mathcal{C}\) the complex \(X(J, s., r)\) as well \(K\) the complex \(X(J, s., r)\) splits as a direct sum of elementary complexes
\[
C^K_r(s.) = \bigoplus X(s., r)K(m_1, \ldots, m_n).
\]
On the other side, for a fixed \(J \in K\) we consider the complex defined by the column of vector spaces
\[
C^K_r(J) = \{ \bigoplus m. \in X(s., r)K((m_1, \ldots, m_n), J) \}_{s. \in S(K)}.
\]
We want to show that each column is an acyclic complex if \(((m_1, \ldots, m_n) \notin T(r) \text{ and a resolution of } K((m_1, \ldots, m_n), J) \text{ otherwise if } (m_1, \ldots, m_n) \in T(r))\).
This is just a combinatorial study, which helped to formulate the statement after an explicit study of the theorem in case \(n = 2 \text{ and } n = 3\). We give a proof based on the following facts:

**Lemma:**

1. Let \(r \geq 0\), then for each \(i \in K\) the sub-complexes
   \[
   C^K_r(W^i_1L) \simeq s(\bigoplus m. \in X(s., r) \text{ and } m_i < 2)K(m_1, \ldots, m_n)L_{s. \in S(K)}
   \]
as well \(C^K_r(\text{IC}(W^i_1L))\) are acyclic. More precisely for \(r > 0\), each column
\[
C^K_r(J)(W^i_1L) = s(C^K_r(J, s.)(W^i_1L))_{s. \in S(K)}
\]
is acyclic.
2. Dually, for \(r < 0\) and for each \(i \in K\) the quotient complexes
   \[
   C^K_r(L/W^i_1L) \simeq s(\bigoplus m. \in X(s., r) \text{ and } m_i \geq 2)K(m_1, \ldots, m_n)L_{s. \in S(K)}
   \]
are acyclic column by column.

**Proof:** We distinguish in \(S(K)\) the subcategory \(S''_i\) whose objects \(s.\) contain \(K\) and \(K - i\). The complement \(S(K) - S''_i\) is a full subcategory of \(S(K)\) since if we delete a subset in \(s. \in S(K) - S''_i\) we still have an object for this subcategory. Hence we sum \(C''_r: = s(C^K_r(s.))_{s. \in S(K) - S''_i}\) is a subcomplex of \(C^K_rL\) whose quotient complex is \(C(S''_i): = s(C^K_r(s.))_{s. \in S''_i}\).

Dually, we consider \(S'''_i \subset S'_i\) whose objects \(s.\) contain \(\{i\}\). The complement \(S(K) - S'''_i\) is a full subcategory of \(S(K)\) since if we delete a subset in \(s. \in S(K) - S'''_i\) we still have an object in this subcategory. Hence we sum \(C'''_r: = s(C^K_r(s.))_{s. \in S(K) - S'''_i}\) is a subcomplex of \(C^K_rL\) whose quotient complex is \(C(S'''_i): = s(C^K_r(s.))_{s. \in S'''_i}\).

**Sublemma:** In the exact sequence
\[
0 \rightarrow C''_r(W^i_1L) \rightarrow C^K_r(W^i_1L)[1] \rightarrow C(S''_i)(W^i_1L)[1] \rightarrow 0
\]
the complexes at each side are acyclic (column by column if \(r > 0\)), so is the middle complex.

Dually, in the exact sequence
\[
0 \rightarrow C'''_r(L/W^i_1L) \rightarrow C^K_r(L/W^i_1L)[1] \rightarrow C(S'''_i)(L/W^i_1L)[1] \rightarrow 0
\]
the complexes at each side are acyclic (column by column if \(r < 0\)), so is the middle complex.
Proof. We write $s$ as $(s’ \supset s_v \cup i \supset s_{v-1} \supset s.’)$ where $i \notin s_{v-1}$ and distinguish in the objects of $S(K)$ two families : $S_1$ whose objects are defined by the $s$ satisfying $s_v \supset s_{v-1}$ (including the case $s_{v-1} = \emptyset$) and $S_1’$ whose objects $s$. satisfy $s_{v-1} = s_v$ (including the case $s_{v-1} = \emptyset$, that is $s_v \cup i = i$).

We form the complexes $C(S’_1 - S’_m): = s[C^K_r(s)]_{s \in S_1’ - S’_m}$ (resp. $C(S_s): = s[C^K_r(s)]_{s \in S_s}$. If we delete $s_v \cup i$ in $s. \in S_1’ - S’_m$ we get an element in $S_1’$, then removing $s_v \cup i$ can be viewed as a morphism $d_{sv \cup i} : C(S_1’ - S’_m) \rightarrow C(S_1)$ and the cone over this $d_{sv \cup i}$ is equal to $C^K_r[1]$.

Now, if we reduce the construction to $W_1L$ and if $s.$ is an object of $S_1’$, the condition $m. \in X(s.,r)$ associated to $s.$ when $s_{v-1} = s_v \neq \emptyset$ (resp. $s_v \cup i$) is $\Sigma j_{s} m_j \leq | s_v | + r - 1$ (resp. $m_i + \Sigma j_{s} m_j \leq | s_v \cup i | + r - 1)$, but precisely when $m_i < 2$ (that is in $W_1L$ the condition for $s_v$ is equivalent to the union of the conditions for $s_v$ and $s_v \cup i$, that is $d_{sv \cup i}$ induces an isomorphism for such object in $S_1’ - S’_m$).

When $s_{v-1} = \emptyset$ and if $r > 0$, the condition $m_i \leq r$ is irrelevant since already $m_i \leq 1$ and $r \geq 1$, so that $d_{sv \cup i}$ induces an isomorphism for all objects in $S_1’ - S’_m$ (if $r = 0$ the difference are complexes $K(m_1, \ldots, m_n)$ with some $m_i = 1$, hence acyclic).

Dually, $S_1’ $ whose objects $s.$ satisfy $s_{v-1} = s_v = \emptyset$, that is $i \in s.$ is contained in $S_1’$, then the cone over the morphism $d_{sv \cup i} : C(S_1’ - S’_m)(L) \rightarrow C(S_1)(L)$ is isomorphic to $C^K_r[1]$. When $m_i > 0$ the condition for $s_v \cup i$ is equivalent to the union of the conditions for $s_v = s_{v-1} = \emptyset$ and $s_v \cup i$, that is $d_{sv \cup i}$ induces an isomorphism for such object in $S_1’ - S’_m$.

Finally we prove $C(S_1’)(W_1L) = 0$. In fact the conditions for $K$ and $K - i$ in any $s. \in S_1’$ are $\Sigma j_{K} m_j = | K | + r$ (resp. $\Sigma j_{K-i} m_j \leq | K - i | + r - 1)$, hence we get by difference $m_i \geq 2$.

Dually, $C(S_1’)(L/W_1L) = 0$. In fact the condition $m_i \leq r$ corresponding to $i \in s. \in S_1’$ is not compatible with $m_i > 0$ when $r < 0$ which ends the proof of the sublemma.

On the otherside, it is easy to check that

Lemma: The complex $C(T(r))$ is contained in each $C^K_r(s)$ that is $T(r) \in X(s.,r)$. Dually, the complex $C(T’(r))$ is contained only in $C^K_r(s)$ for $s. = K$.

We check the condition $\forall s. \in s., \Sigma i_{s} m_i \leq | s. | + r - 1$ for all $m. \in T(r)$ by induction: $\Sigma j_{K} m_j = | K | + r \Rightarrow \forall A = K - k \subset K, \Sigma j_{A} m_j \leq | A | + r - 1$ by substracting $m_k > 1$. If this is true for all $A : | A | = a$ then $\forall B = A - k \subset A, \Sigma j_{B} m_j \leq | B | + r - 2$ as well.

Dually, the condition for $K$, $\Sigma j_{K} m_j = | | K | + r \Rightarrow \forall A = K - k \subset K, \Sigma j_{A} m_j \leq | A | + r - 1$ by substracting $m_k < 1$. If this is true for all $A : | A | = a$ then $\forall B = A - k \subset A, \Sigma j_{B} m_j \geq | B | + r - 1$ as well.

Finally, we form the complex $C(r) = s[C(T(r))_{s \in S(K)} \subset C^K_r(L)$ and we deduce

Lemma: i) The quotient $(C^K_r, C_r(L/C(r))) \cong 0$ is acyclic.

ii) For any maximal index $s. \in S(K)$, the embedding $C(T(r)) \subset C^K_r(s.)$ induces a quasi-isomorphism $C(T(r)) \cong C^K_r(L).

iii) Dually, the quotient $[C^K_r, C_r(L/C(T’(r)))(s. = K)] \cong 0$ is acyclic.

Proof. i) Since any element of the quotient can be represented by an element in a subcomplex $K(m_1, \ldots, m_n)$ with some $m_i < 2$ we can apply the lemma above for some $W_1L$.

ii) $d_{sv \cup i}$ induces an isomorphism on the complexes obtained as sum of $C(T(r))$ over $S_1’ - S’_m$ and $S_1$, hence the cohomology of $C(r)$ comes from $C(S_1’)$.

All elements $s. \in S_1’$ contain $K \supset K - i$, so we can repeat the same arguments in the category $S(K - i)$ but for $j \neq i$, so (ii) follows by induction.

iii) The assertions for $C^K_rICL$ and $C^K_rQL$ (20) follow from the the corresponding isomorphisms $C(T(r)L) \cong (C(T(r))ICL$ and $(C(T’(r))) \cong (C(T’(r))ICL$. 

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Remark (duality). Given a polarised nilpotent orbit \((L, N_i(i \in M), P)\), the local duality induces an isomorphism:
\[
d^K_r : C^K_r L[2 | K | -1] \simeq \text{Hom}_Q(C^K_r L, Q)
\]
hence \(H^i(C^K_r L)[2 | K | -1]) = H^{i+2[K]-1} \simeq \text{Hom}_Q(H^{-i}(C^K_r L), Q)\) and for \(i = 1- | K |:
\[
d^K_r : H^{|K|}(C^K_r L) \simeq \text{Hom}_Q(H^{|K|}(C^K_r L), Q)
\]

The duality is constructed as follows: For each \(s\) we define \(C(s) = \{ s' \in S(K) : | s' | + 1 \text{ s.t. } s.s' \text{ is maximal} \}\), that is to say \(s\) is complementary to \(s'\). Except that both must contain \(K\), then we define: \(P^*: C_r(J, s) \otimes C_r(J', s') \rightarrow Q\) as \(P^*(a, b) = P(a, b)\) for \(J' = K - J\) and \(s', \in C(s)\) and zero otherwise \((P^*\) is non zero on \(C_r(J, s) \otimes (\oplus_{s' \subseteq C(s)} C_r(K - J', s')).\)

It can be checked that the induced morphism \(P^*: C^K_r L[2 | K | -1] \rightarrow \text{Hom}_Q(C^K_r L, Q)\) commutes with differentials.

The relation between \(C^K_r L\) and \(C^{KM}_r L\)

The following result will be important in the general proof of the decomposition of \(Gr^W_r \Omega^* L\) as direct sum of intersection complexes.

Proposition: Let \(H = H^*(C^K_r L)\), considered as a nilpotent orbit with indices \(i \in M - K\), then
i) We have \(C^{KM}_r L \simeq W_{-1} \Omega^*(H)\)

ii) For \(r \geq 0\), \(C^{KM}_r L \simeq C^{KM}_r QL\)

Proof. i) We can write \((K^+ \times S(K) \times (M - K)^+ \times S(M - K)) \simeq M^+ \times S_K(M)\), with the correspondence \((J, s, J', s') \rightarrow ((J, J'), (s' \cup K, s))\) then using the relations:
1) \(a_{s(J, J'), r - 1} = a_{s(J, r - 1)}\) when \(s(J, J') \in K\)
2) \(a_{s(J, J'), r - 1} = a_{s(J', r - 1)} + a_{K(J, r)}\) and
\[
W^{s(J, J'), r - 1}_{\alpha, s(J, J'), r - 1}(Gr^W_{\alpha, K(J, r)}) = W^{s(J, J'), r - 1}_{\alpha, J, r}(Gr^W_{\alpha, K(J, r)})\]
\(\text{since } W^{s(J, J'), r - 1}_{\alpha, s(J, J'), r - 1} \text{ is relative to } W^K\)

we find \(C^{KM}_r L = s\left(\cap K_{\neq \lambda} \subseteq (s' \cup K, s)\right) W^{s(J, J'), r - 1}_{\alpha, s(J, J'), r - 1} G_{\alpha, K(J, r)} L \simeq C^{KM}_r QL\)
\(\text{if } \alpha = 1 \text{ and } K_{\neq \lambda} \subseteq (s' \cup K, s)\)

\(s(\cap K_{\neq \lambda} \subseteq (s' \cup K, s)) W^{s(J, J'), r - 1}_{\alpha, s(J, J'), r - 1} G_{\alpha, K(J, r)} L \simeq C^{KM}_r QL\)

where \(\cap K_{\neq \lambda} \subseteq (s' \cup K, s)\) is defined as above for each subset of \(L\).

This formula shows that \(C^{KM}_r L\) is constructed in two times, once as \(C^K\) over \(K^+ \times S(K)\) (that is a space normal to \(Y_K\) and once as a weight filtration over \((M - K)^+ \times S(M - K)\) (that is the space \(Y_K\)).

ii) Let \(H' = H^*(C^K_r IC(L))\) then the above proof apply word for word to show (notation 18):
\(C^{KM}_r IC(L) \simeq W_{-1} \Omega^*(H')\). For \(r \geq 0, H' = 0\), hence \(C^{KM}_r IC(L) \simeq 0\) and the isomorphism in (ii) follows since \(C^{KM}_r Q(L) \simeq C^{KM}_r L/C^{KM}_r IC(L)\).

II. Local decomposition.

Theorem (decomposition): For a nilpotent orbit \(L\) of dimension \(n\), there exist canonical injections of \(C^{KM}_r L\) in \(Gr^W_r (\Omega^* L)\) which decomposes in the category of perverse sheaves (up to a shift in
degrees) as a direct sum

\[ \text{Gr}_r^W(\Omega^*L) \simeq \bigoplus_{K \subset M} C_r^{KM}L. \]

Moreover \( \text{Gr}_r^W(\Omega^*L) \simeq 0 \) is acyclic.

To carry out the proof by induction on \( n \), we use only the property \( \text{Gr}_r^W(\Omega^*L) \simeq 0 \) in dimension \( n - 1 \) to get the decomposition in \( \text{dim}~n \), then we use the fact that \( C_r^K L \) for all \( K \) is acyclic to get again \( \text{Gr}_r^W(\Omega^*L) \simeq 0 \) in dimension \( n \) so to complete the induction step. For \( n = 1, K \) and \( M \) reduces to one element 1 and the theorem reduces to

\[ \text{Gr}_r^W \simeq C_r^L = \text{Gr}_{r+1}^W N_1 \text{Gr}_{r-1}^W L \]

By the elementary properties of the weight filtration of \( \text{Gr}_r^W \), it is quasi-isomorphic to \( \text{Gr}_{r+1}^W (L/N_1 L)[-1] \) if \( r > 0 \), \( \text{Gr}_{r+1}^W (\ker N_1 : L \to L) \) if \( r < 0 \) and \( \text{Gr}_0^W L \simeq 0 \).

For higher dimensions, the proof is carried in various steps.

The complexes \( A_r^{KM}, B_r^{KM} \) and \( D_r^{KM} \)

Fixing the \( \text{dim}~n \), the proof is by induction on the length \( | K | \) of \( K \) in \( M \). For \( r \in \mathbb{Z} \), \( K \) fixed and \( (J,s) \in M^+ \times S_K M \) we consider the space \( V(J,s) = \bigcap_{s \in S_K} W_{a(s),(J,s) M}^r L \) and the filtrations of \( V \):

\[ V_t^1(J,s) = W_{a(J,s) M}^r L, \quad V_t^2(J,s) = \bigcap_{s \in S_K} W_{a(s),(J,s) M}^r L \]

so that \( V_t^1(J,s) \cap V_t^2(J,s) = \bigcap_{s \in S_K} W_{a(s),(J,s) M}^r L \).

By summing over \( (J,s) \), we define the complexes

\[ A_r^{KM} = s[Gr_0^W W_{a(K,J,r-1)}^r \bigcap_{s \in S_K} W_{a(s),(J,s) M}^r L](J,s) \in M^+ \times S_K M \]

\[ B_r^{KM} = s[Gr_0^W W_{a(K,J,r-1)}^r \bigcap_{s \in S_K} W_{a(s),(J,s) M}^r L](J,s) \in M^+ \times S_K M \]

\[ D_r^{KM} = s[Gr_0^W W_{a(K,J,r) M}^r \bigcap_{s \in S_K} W_{a(s),(J,s) M}^r L](J,s) \in M^+ \times S_K M \]

Lemma: For all \( K \subset M \), there exists a natural quasi-isomorphism

\[ B_r^{KM} L \oplus C_r^{KM} L \cong A_r^{KM} L \]

The proof of this lemma reduces to two sublemmas.

Sublemma: For all \( K \subset M \), there exists an exact sequence of complexes

\[ 0 \to B_r^{KM} \oplus C_r^{KM} \to A_r^{KM} \to D_r^{KM} \to 0 \]

The proof is based on the following elementary remark:

Let \( W^i \) for \( i = 1, 2 \) be two increasing filtrations on an object \( V \) of an abelian category and \( a_i \) two integers, then we have an exact sequence:

\[ 0 \to W_{a-1}^2 W_{a1}^1 \oplus W_{a2}^1 \to W_{a1}^1 \cap W_{a2}^1 \to W_{a2}^1 \cap W_{a1}^2 \to 0 \]

We apply this remark to the space \( V(J,s) = \bigcap_{s \in S_K} W_{a(s),(J,s) M}^r L \) and the filtrations \( W^1 \) and \( W^2 \) of \( V \) for \( a_1 = 0 \) and \( a_2 = 0 \), then we deduce from the above sequence an exact sequence of vector spaces:

\[ 0 \to Gr_0^W W_{a(K,J,r-1)}^r (V) \oplus W_{a2}^1 (J,s) Gr_0^W W_{a(K,J,r)}^r (V) \to W_{a(K,J,r)}^r \cap W_{a2}^1 (V) \to 0 \]

The sublemma follows by summing over \( J, s \).

Next we prove by induction on \( n \) for the general theorem, (not only the lemma)

Sublemma: \( D_r^{KM} \cong 0 \).
Proof. The idea of the proof is to write $D_{r}^{KM}$ as $G_{r}^{W}(\Omega^{*}(C_{r}^{K}L)) \simeq 0$ where $C_{r}^{K}L$ is viewed as a nilpotent orbit on $M - K$ (that is the fiber of a local system on $Y_{M-K}$) and use the induction to prove it is zero. We can either use that $C_{r}^{K}L$ is reduced to its unique non zero cohomology or as well prove the acyclicity for each term in $C_{r}^{K}L$, what we do as follows.

We simplify the notation from $W_{t}^{2}$ above to $W_{t}^{0}(K,J,s.) := \cap K_{s,\lambda} \in s. W_{a_{s}^{\lambda}}(J, r + t)G_{r}^{W}(K)\cap (\lambda_{s,\lambda} \in s. W_{a_{s}^{\lambda}}(J, r - 1) L)$ so to write the complex as $D_{r}^{KM} L = s(G_{r}^{W}(K,J,s.))_{(J,s.) \in M + s. K}$, then we use the decomposition of $S_{K}(M)$ to rewrite $W_{t}^{0}$ as $W_{t}^{0}(K,J,s. : (K \cup s', s.)) = \cup K_{s,\lambda} \in s'. W_{a_{s}^{\lambda}}(J, r + t)G_{r}^{W}(K)\cap (\lambda_{s,\lambda} \in s. W_{a_{s}^{\lambda}}(J, r - 1) L) = \cup K_{s,\lambda} \in s'. W_{a_{s}^{\lambda}}(J', r)G_{r}^{W}(K)\cap (\lambda_{s,\lambda} \in s. W_{a_{s}^{\lambda}}(J, r - 1) L)$ and the complex $D_{r}^{KM} L = s[G_{r}^{W}(K,J,s. : (J,s.'))(J,s.) \in M + s. K \times (M - K)^{+} s. (M - K)]$ as a sum in two times over $(J,s. : (K \cup s'. s.)) \in K^{+} \times s. K$ and $(J', s.' : (M - K)^{+} s. (M - K))$. For a fixed $(J,s.)$ we consider $L(r,J,s.) = G_{r}^{W}(K,J,r)\cap (\lambda_{s,\lambda} \in s. W_{a_{s}^{\lambda}}(J, r - 1) L)$ and the filtration by subspaces $L(r,J,s.) := \cup K_{s,\lambda} \in s'. W_{a_{s}^{\lambda}}(J', r)G_{r}^{W}(K)\cap (\lambda_{s,\lambda} \in s. W_{a_{s}^{\lambda}}(J, r - 1) L)$ and finally the complex $D_{r}^{KM} L = s[D(M - K)(L(r,J,s.))(J,s.'))(J,s.) \in M - K)^{+} s. (M - K)$. By construction $D_{r}^{KM} L = s[\cup D(M - K)(L(r,J,s.))(J,s.'))(J,s.) \in M - K)^{+} s. (M - K)]$.

We prove by induction on $n$: $D(M - K)(L(r,J,s.)) \simeq 0$. First we embed $D(M - K)(L(r,J,s.))$ in the complex $D'(M - K)(L(r,J)) := s[G_{r}^{W}(K,J))_{(J,s.'))(J,s.) \in M - K)^{+} s. (M - K)]$ using the embedding $L(r,J,s.) \subset G_{r}^{W}(K,J,r)$. Now we introduce the weight filtration $W$ on the combinatorial DeRham complex $\Omega^{*}G_{a_{r}^{W}(K,J,r) L}$ for the nilpotent orbit $G_{a_{r}^{W}(K,J,r) L}$ of dimension strictly less then $n$ and weight $a_{r}(J,r)$ and we notice that $D'(M - K)(L(r,J)) \simeq G_{r}^{W}(\Omega^{*}(G_{a_{r}^{W}(K,J,r) L}) \simeq 0$ which is zero by induction in dimension $n - 1$. Now $D'(M - K)(L(r,J))$ is a complex of $MHS$ and $W_{a_{r}^{W}}$ (up to a shift) is a filtration by subcomplexes of $MHS$, so we deduce by strictness that for each $r,J,s.$ the complex $D(M - K)(L(r,J,s.)) \simeq 0$ is zero. This ends the proof of the sublemma and hence the lemma.

Proof of the decomposition theorem

For each $i \in \mathbb{N}$ we define a map $\varphi_{i} : S(M) \rightarrow \mathcal{P}(M)$ to the subsets of $M$ such that $M \supset \varphi_{i}(s) = \text{Sup}(s_{\lambda} : s_{\lambda} \leq i)$ and for each $(J,s.) \in M^{+} s. (M - K)$, the filtration with index $t$ of $L$, $W_{t}^{2}(\varphi_{i}(s), J, s.)) := \cap s_{\lambda} \in s. W_{a_{s}^{\lambda}}(J, r + t)\cap (\lambda_{s,\lambda} \in s. W_{a_{s}^{\lambda}}(J, r - 1) L),$ We define $G_{i}(J,s.) := G_{i}^{W_{t}^{2}(\varphi_{i}(s), s.))L$ then we consider the complex $G_{i}(s) = s(G_{i}(J,s.)L)_{J \subset M} = s(G_{i}^{W})_{J \subset M} = s(G_{i}(s))_{s \in S(M)}$.

In particular, when $\varphi_{i}(s) = \varnothing$, $G_{i}(s) = G_{r}^{W}(L,s.)$ so that for $i \leq 0$, $G_{i}^{SM} L = G_{r}^{W_{SM}} L$ and when $i = M - 1, G_{i}^{SM} L = C_{r}^{M} L$. Hence the proof of the decomposition theorem will follows from the
Lemma.

\[ G^S_{i+1} \cong G^S_i + C^K M \]

Now in order to compare \( G^S_i L \) and \( G^{S+1}_{i+1} L \), we consider the category \( S^i(M) = \{ s. \in S(M) : s. \} \) which is not a subcategory of \( S(M) \) but \( S(M) - S^{i+1}(M) \) is a subcategory such that the restrictions of \( G_i \) and \( G_{i+1} \) define two subcomplexes: \( G'_i = s(G_i(s.))_{s \in S(M) - S^{i+1}(M)} \subset G^S_i L \) and \( G'_{i+1} = s(G_{i+1}(s.))_{s \in S(M) - S^{i+1}(M)} \subset G^S_{i+1} L \). We have \( G'_{i+1} = G'_{i} \) since \( \varphi_i = \varphi_{i+1} \) on \( S(M) - S^{i+1}(M) \).

The next step is to compute the quotient complexes, for this we remark: \( S^{i+1}(M) \cong \oplus[K=i+1] S(K)(M) \) and \( \varphi_{i+1}(s.) = K \) for \( s. \in S_K M \), then:

\[ G^{S+1}_{i+1}(M) = G^S_{i+1} L / G'_{i+1} \cong s(G_{i+1}(s.))_{s \in S^{i+1}(M)} \cong \oplus[K=i+1] s(G_{i+1}(s.))_{s \in S_K(M)} \cong \oplus[K=i+1] B^K M \]

On the other side, when \( s. \in S_K M \) where \( K \) \( = i+1 \), \( G_i(J, s.) = G_0 W^1(\varphi_i(s.), J, s.) L \) and \( G^{S+1}_i(M) = s(G_i(s.))_{s \in S_K M} = A^K M \), so that

\[ G^{S+1}_i(M) = G^S_i L / G'_i \cong s(G_i(s.))_{s \in S^{i+1}(M)} \cong \oplus[K=i+1] s(G_i(s.))_{s \in S_K(M)} \cong \oplus[K=i+1] A^K M. \]

Now we deduce from the quasi-isomorphism \( B^K M \oplus C^K M \cong A^K M \) that \( G^{S+1}_i = A^K M \cong G'_{i+1} \oplus C^K M \) hence \( G^S_i / G'_i \cong (G^S_{i+1} / G'_{i+1}) \oplus C^K M \), which proves the lemma since \( G'_i \cong G'_{i+1} \).

III. Global construction of the weight filtration.

For each subset \( s_\lambda \subset I \) such that \( s_\lambda \neq \emptyset \), we write \( W^{s_\lambda} = W(\Sigma_{i \in s_\lambda} N_i) \) for the filtration by subbundles defined by the nilpotent endomorphisms of the restriction \( \mathcal{L}_{Y_\lambda} \) of \( \mathcal{L}_X \) to \( Y_\lambda^* \), inducing also by restriction and for each subset \( K \supset s_\lambda \) a filtration on \( \mathcal{L}_{Y_K} \). Since \( (\Omega^*_{X_\lambda}(\log Y)^* \otimes \mathcal{L}_{Y_\lambda}^*)_g \) is acyclic if there exists an index \( j \in M \) such that \( \alpha_j \neq 0 \) (see the formula (11) and the remark below), we can suppose from now on the local system unipotent.

Definition (the weight and Hodge filtrations). The weight filtration is defined for \( \mathcal{L} \) unipotent, on the following combinatorial logarithmic complex

\[ \Omega^*(\mathcal{L}) = s(\Omega^*_{X_\lambda}(\log Y)^* \otimes \mathcal{L}_{X_\lambda})_{s \in S} \]

as follows: let \( M \subset I \), \( | M | = p \) and \( y \in Y^*_M \), then in terms of a set of \( n \) coordinates \( y_i, i \in [1, n] \) where we identify \( M \) with \([1, p]\) on an open set \( U_y \cong D^j M \times D^{n-p} \) containing \( y \) and a section \( f = (f^s.)_{s \in S} \)

\[ f^s. = \sum_{J \subset M, J' \subset M} \# f^s. \frac{dy_J}{y_J} \wedge dy_{J'} \]

\[ f = (f^s.)_{s \in S} \in W_r(\Omega^*(\mathcal{L}))_{/U_y} \Leftrightarrow \forall J, N \subset M, f_{J, N}^s. / Y_N \cap U_y \in \bigcap_{s_\lambda \subset s, s_\lambda \subset N} W^{s_\lambda}_{\alpha_\lambda(J, \gamma)}(\mathcal{L} / Y_N \cap U_y) \]

By convention we let for all integers \( r \), \( W_r / X - Y = \Omega^*(\mathcal{L}) / X - Y \), so that \( W_r \) is the direct image for \( r \) big enough and the extension by zero for \( r \) small enough. It is a filtration by subcomplexes.
of analytic subsheaves globally defined on $X$. The Hodge filtration $F$ is constant in (s.) and deduced from Schmid’s extension to $\mathcal{L}_X$

$$F^p(s.) = 0 \rightarrow F^p \mathcal{L}_X \ldots \rightarrow \Omega^i_{X_s}(\text{Log} Y) \otimes F^{p-i} \mathcal{L}_{X_s} \rightarrow \ldots \rightarrow F^p = s(F^p(s.))_{s \in S}$$

**Theorem:** Consider a unipotent local system $\mathcal{L}$ underlying a variation of polarised Hodge structures of weight $m$; then the complex

$$(\Omega^*(\mathcal{L}), W[m], F)$$

with the filtrations $W$ and $F$ defined above satisfy the decomposition and purity properties. More precisely, for all subset $K \subset I$ and all integers $r > 0$ (resp. $r < 0$), let $(\mathcal{L}_K^r, W, F)$ denotes the bifiltered local system underlying a polarised VHS on $Y^*_K$ of weight $r-|K|+m$ (resp.$r+|K|+m$) and of general fiber $(H^{1K}(C_r^K L), W, F)$ of weight induced by $W^{r}|_{r-|K|+m}$ and $F$ defined by $L$ (resp. $(H^{1K})^{-1}(C_r^K L), W, F)$ for $r < 0$ of weight induced by $W^{r}|_{r+|K|+m}$. Then we have the following decomposition into intermediate extensions (up to shift in degrees) of (VHS) $L^r_K$ compatible with the local decomposition

$$(Gr_{r+m}^W \Omega^* \mathcal{L}, F) \simeq \bigoplus_{K \subset I} J^K_r (\mathcal{L}_K^r[-|K|], W[2-|K|], F_{[-|K|]}, \text{for } r > 0 \text{ and } j^K : Y^*_K \rightarrow Y^*_I)$$

$$(Gr_{r+m}^W \Omega^* \mathcal{L}, F) \simeq \bigoplus_{K \subset I} J^K_r (\mathcal{L}_K^r[-|K|], W[-1], F), \text{for } r < 0$$

that is for $r \geq 0$ the weight is coincides with the weight for Hodge structures but for $r < 0$ the true weight for Hodge structures is $r + m + 1$.

iii) The projection on the quotient complex $(\Omega^*(\mathcal{L})/j_* \mathcal{L}, W[m], F)$ with the induced filtrations, induces a filtered quasi-isomorphism on $(Gr_{r+m}^W \Omega^* \mathcal{L}, F)$ for $r > 0$.

Proof. The decomposition of $(Gr_{r+m}^W \Omega^*(\mathcal{L}, F))$ reduces near a point $y \in Y^*_M$ to the local decomposition of $Gr_{r+m}^W \Omega^*(\mathcal{L})$ for the nilpotent orbit $L$ defined at the point $y$ by the local system since $C_r^K L$ is precisely the fiber of $j_* L^r_K[-|K|] \rightarrow yr$ (resp. $j_* L^r_K[-|K|] \rightarrow yr$) for $r < 0$. The count of weight takes into account for $r > 0$ the residue in the isomorphism with $L$ that shifts $W$ and $F$ but also the shift in degrees, while for $r < 0$ there is no residue but only a shift in degrees, the rule being as follows:

Let $(K, W, F)$ be a mixed Hodge complex then for all $m, h \in \mathbb{Z}$, $(K', W', F') = (K[m], W[m-2h], F[h])$ is also a mixed Hodge complex.

The same proof apply for $r = 0$, hence $W_{-1} \simeq \mathcal{W}_0$ is isomorphic to the intermediate extension of $\mathcal{L}$ by Kashiwara and Kawai’s formula, that we prove below. The assertion (iii) follows from the assertion (iii) in the purity theorem corresponding to a result on $C_r^MQL$.

**Proof of Kashiwara and Kawai’s formula:** $j_* \mathcal{L}[2n] \simeq \mathcal{W}_0 \Omega^*(\mathcal{L}[2n])$.

In this subsection we give a proof of the formula of the intermediate extension of $\mathcal{L}[2n]$, announced in [26], which is in fact the subcomplex $\mathcal{W}_0 \Omega^*(\mathcal{L}[2n])$. It follows easily from the local decomposition of the graded parts of the weight filtration, by induction on the dimension $n$.

**Theorem.** The subcomplex $\mathcal{W}_0 \Omega^*(\mathcal{L}[2n])$ is quasi-isomorphic to the intermediate extension of $\mathcal{L}[2n]$.

The proof of this theorem is by induction on the dimension $n$. It is true in dimension $1$ and if we suppose the result true in dimension strictly less than $n$, we can apply the result for local
systems defined on open subsets of the closed sets $Y_K$, namely the local system $\mathcal{L}_r^K[-| K |]$ for $r > 0$ (resp. $\mathcal{L}_r^K[1 - | K |]$) for $r < 0$) whose fiber at each point $y \in Y_K$ is quasi-isomorphic to $C_r^K L$. Let $j^K : Y_K^* \to Y_K$ be the open embedding in $Y_K$ and consider the associated DeRham complex $\Omega^*(\mathcal{L}_r^K)$ on $Y_K$ whose weight filtration will be denoted locally near a point in $Y_M$ by $\mathcal{W}_M-K$ for $K \subset M$; then by the induction hypothesis we have at the point $y$: $\mathcal{W}_1 \Omega^* L \simeq \mathcal{W}_0 \Omega^* L$ is also quasi-isomorphic to the fiber of the intermediate extension of $\mathcal{L}$, that is

$$\forall r > 0, C_r^K M(L) \simeq (j_r^K \mathcal{L}_r^K[-| K |])_y \simeq \mathcal{W}_1^{-M-K} C_r^K L$$

and similarly for $r < 0$.

We use the following criteria characterising intermediate extension [17]:

Consider the stratification defined by $Y$ on $X$ and the middle perversity $p(2k) = k - 1$ associated to the closed subset $Y^{2k} = \cup_{| K | = k} Y_K$ of real codimension $2k$. Let $Y^{2k-1} = Y^{2k}$ and $p(2k-1) = k - 1$. For any complex of sheaves $S$ on $X$ which is constructible with respect to the stratification, let $S^{2k} = S^{2k-1} = S | X - Y^{2k}$ and consider the four properties:

a) Normalisation: $S | X - Y^2 \cong \mathcal{L}[2n]$

b) Lower bound: $H'(S) = 0$ for all $i < -2n$

c) vanishing condition: $H^m(S^{2k+1}) = 0$ for all $m > k - 2n$

d) dual condition: $H^m(j^{2k} S^{2(k+1)}) = 0$ for all $k \geq 1$ and all $m > k - 2n$ where $j^{2k} : Y^{2k} - Y^{2(k+1)} \to X - Y^{2(k+1)}$ is the closed embedding, then $S$ is the intermediate extension of $\mathcal{L}[2n]$.

In order to prove the result for $n$ we check the above four properties for $\mathcal{W}_0 \Omega^*([2n])$. The first two are clear and we use the exact sequences

$$0 \to \mathcal{W}_{r-1} \to \mathcal{W}_r \to Gr^V_r \to 0$$

to prove d) (resp. c) by descending (resp. ascending) indices from $\mathcal{W}_r$ to $\mathcal{W}_{r-1}$ for $r > 0$ (resp. $r - 1$ to $r$ for $r < 0$) applying at each step the inductive hypothesis to $Gr^V_r$.

Proof of d). The dual condition is true for $r$ big enough since then $\mathcal{W}_r$ coincides with the whole complex, that is the higher direct image of $\mathcal{L}[2n]$ on $X - Y$. Now we apply d) on $Y_{K'}$ with $| K' | = k'$ for $j' : Y^{2k} \cap \cap Y_{K'} - Y^{2(k+1)} \cap Y_{K'} \to Y_{K'} - Y^{2(k+1)} \cap Y_{K'}$, where we suppose $k > k'$ (notice that $Y_k^{2k} \cap Y_{K'} = (Y \cap Y_{K'})_{2(k-k')}$, then for $S'$ equal to the intermediate extension of $\mathcal{L}_r^{K'}[2n - 2k']$ on $Y_{K'}$ we have the property $H^m(j^{2k} S^{2(k+1)}) = 0$ for all $(k-k') \geq 1$ and all $m > k - k' - 2(n-k') = k + k' - 2n$ which gives for $S'[k]$ on $X$: $H^m(j^{2k} S^{2(k+1)}[k]) = 0$ for all $k > k'$ and all $m > k - 2n$, hence d) is true.

If $k = k'$, then $Y^{2k} \cap Y_{K'} = Y_{K'}$ and we have a local system in degree $k' - 2n$ on $Y_{K'} - Y^{2(k+1)} \cap Y_{K'}$ hence $d$ is still true and for $k < k'$, the support $Y_{K'} - Y^{2(k+1)} \cap Y_{K'}$ of $S'$ is empty. From the decomposition theorem and the induction, this argument apply to $Gr^V_r$ and hence apply by induction on $r \geq 0$ to $\mathcal{W}_0$ and also to $\mathcal{W}_{1}$.

Proof of c). Dually, the vanishing condition is true for $r$ small enough since then $\mathcal{W}_r$ coincides with the extension of zero of $\mathcal{L}[2n]$ on $X - Y$.

Now we use the filtration for $r < 0$, for $S'$ equal to the intermediate extension of $\mathcal{L}_r^{K'}[2n - 2k']$ on $Y_{K'}$ we have for $k > k'$: $H^m(S'[2(k+1)]) = 0$ for all $m > k + k' - 2n$, which gives for $S'[k+1]$, $(r < 0)$ on $X$: $H^m(S^{2(k+1)}) = \mathcal{H}^m(S^{2k+1}) = 0$ for all $m > k - 1 - 2n$. If $k = k'$, then $S'[k+1]$ is a local system in degree $-2n + k - 1$ on $Y_{K'} - Y^{k+1}$ and for $k < k'$, $Y_{K'} - Y^{k+1}$ is empty.
The method to compute $\Psi_f \eta$ simple associated complex is quasi-isomorphic to $\Psi_u I$. The weight filtration on the nearby cycles of the path.

**Corollary:** If we suppose $X$ proper and we replace the filtration $W$ by $W''$ with $W''_i = W_i$ for $i \geq 0$ and $W''_{-1} = 0$, then the bifiltered complex

$$(\Omega^*(L), W''[m], F)$$

is a mixed Hodge complex.

3. The complex of nearby cycles $\Psi_f (L)$.

Let $f : X \to D$ and suppose $Y = f^{-1}(0)$; the definition of the complex of sheaves of nearby cocycles on $Y$ is given in [11]; its cohomology fiber at a point $y$ equals the cohomology of the Milnor fiber $F_y$ at $y$ in $Y$. The monodromy $T$ induces an action on the cohomology $H^i(\Psi_f(L)) \simeq H^i(F_y, \mathcal{L})$ and on the complex itself viewed in the abelian category of perverse sheaves. It is important to point out that the action on the complex is related to the action on cohomology through a spectral sequence and precisely in our subject we need to use the weight filtration on the complex itself and not on its cohomology.

The aim of this section is to describe the weight filtration on $\Psi_f (L)$. This problem is closely related to the weight filtration in the open case since there exists a close relation between $\Psi_j^f (L)$, the direct image $j_* L$ and $j_! L$ as explained in [2] (and previously in a private letter by Deligne and Gabber).

**Proposition [2]:** Let $\mathcal{N} = \text{Log} T^n$ denotes the logarithm of the unipotent part of the monodromy, then we have the following isomorphism in the abelian category of perverse sheaves

$$j_* L / j_! L \simeq \text{Coker}(\mathcal{N} : \Psi_j^f (L) \to \Psi^f_j (L))[-1]$$

The filtration $W(\mathcal{N})$ on $\Psi_j^f (L)$ induces a filtration $W$ on $\text{Coker} \mathcal{N} / \Psi^f_j (L)$, hence on $j_* L / j_! L$.

The induced filtration on $j_* L / j_! L$ is independant of the choice of $f$. For a rigorous proof one should use the result of Verdier [34]. To prove the independence of $f$ we can use a path in the space of functions between two local equations $f$ and $f'$ of $Y$ and defines by parallel transport an isomorphism between $\Psi_f (L)$ and $\Psi_{f'} (L)$; modulo $\text{coker} \mathcal{N}$, this isomorphism is independent of the path.

I. The weight filtration on the nearby cycles $\Psi_f (L)$

The method to compute $\Psi_f$ as explained in [11] uses the restriction $i_Y^* j_* L$ of the higher direct image of $L$ to $Y$ and the cup-product $H^i(X^*, \mathcal{L}) \otimes H^1(X^*, \mathcal{Q}) \xrightarrow{\eta} H^{i+1}(X^*, \mathcal{L})$ by the inverse image $\eta = f^* c \in H^1(X^*, \mathcal{Q})$ of a generator $c$ of the cohomology $H^1(D^*, \mathcal{Q})$. Thus one defines a morphism (of degree 1), $\eta$: $i_Y^* j_* L \to i_Y^* j_* [1]$ such that $\eta^2 = 0$ so to get a double complex whose simple associated complex is quasi-isomorphic to $\Psi^f_j (L)$, the unipotent part of $\Psi_f (L)$ under the monodromy action $T$

$$\Psi^f_j (L) \simeq s(i_Y^* j_* L[p], \eta)_{p \leq 0}$$

In order to get the full $\Psi_f (L)$ (not only the unipotent part under the action of $T$) Deligne introduced local systems of rank one $\mathcal{V}_\beta$ on the disc with monodromy $e(\beta) = \exp(-2i\pi \beta)$ and proved the following isomorphism

$$\Psi_f (L) \simeq \oplus_{\beta \in \mathbb{C}} \Psi^f_j (L \otimes f^{-1} \mathcal{V}_\beta)$$
When \( \mathcal{L} \) is quasi-unipotent we need only to consider \( \beta \in \mathbb{Q} \cap [0,1] \). Moreover, near a point \( y \in Y \) such that \( f = \prod_{j \in M} z_j^{\alpha_j} \), the tensor product \( \mathcal{L}^{(\alpha)} \otimes f^{-1} \mathcal{V}_\beta \) is unipotent near \( y \) if and only if \( \forall j \in M, \alpha_j + n_j \beta \in \mathbb{N} \), then

\[
(23) \quad \Psi_f (\mathcal{L}^{(\alpha)}) \simeq \bigoplus_{\beta \in S} \Psi_{\mathcal{L}}(\mathcal{L}^{(\alpha)} \otimes f^{-1} \mathcal{V}_\beta), \quad S = \{ \beta \in \mathbb{C} : \forall j \in M, \alpha_j + n_j \beta \in \mathbb{N} \}.
\]

Due to this formula, the problem can be reduced later in the article to study the unipotent part \( \Psi_f^u \). We recall that in order to construct \( \mathcal{L}_X \) we need to choose a section as follows

Definition: We define \( \tau \) as the section of \( \pi : \mathbb{C} \to \mathbb{C} / \mathbb{Z} \) such that \( \text{Re}(\tau) \in [0,1] \).

Local description. Near a point \( y \in Y \), where \( f = \prod_{i=1}^n z_i^{n_i} \) for non zero \( n_i \), in DeRham cohomology \( \eta = f^*([\frac{1}{n_i}]) = \prod_{i=1}^n n_i \frac{dz_i}{z_i} \). The morphism \( \eta \) on \( \Omega(L, D + N, \mathcal{V}) \) is defined by \( \varepsilon_{ij} n_i I : L(i, -i_j) = L \to L = L(i) \) where \( \varepsilon_{ij} \) is the signature of the permutation which order strictly \( i, -i_j \) for various \( i_j \). For each complex number \( \beta \), we consider the following complexes where \( \mathcal{L}^{(\alpha)} \) is the intersection of the eigenspaces for \( T^*_\mathcal{L}, i \in [1, n] \) with eigenvalues \( e(\alpha_i) \).

\[
(24) \quad \Psi_{\mathcal{L}}^\beta (L) = \bigoplus_{\alpha} \Omega(L^{(\alpha)}, \tau(\alpha_i + \beta n_i) I d + N_i)_{i \in [1, n]} [p], \quad p \leq 0
\]

where \( \eta : \Psi_{\mathcal{L}}^\beta (L) \to \Psi_{\mathcal{L}}^{\beta+1}(L) \) is a complex morphism satisfying \( \eta^2 = 0 \), the \( (\Psi_{\mathcal{L}}^\beta, \eta) \) form a double complex for \( p \leq 0 \). Let \( \Psi_{\mathcal{L}}^\beta (L) \) denotes the associated simple complex. In order to take into account the action of \( N = -\frac{1}{2i} \pi \text{Log} T^u \) we write after Kashiwara, \( L[Np] \) for \( L[p] \) and \( L[N^{-1}] \) for the direct sum over \( p \), so that the action of \( N \) is just multiplication by \( N \).

\[
(25) \quad \Psi_{\mathcal{L}}^\beta (L) = s(\Psi_{\mathcal{L}}^\beta (L), \eta)_{p \leq 0} \simeq \bigoplus_{\alpha} \Omega(L^{(\alpha)}[N^{-1}], \tau(\alpha_i + \beta n_i) I d + N_i - n_i N)_{i \in [1, n]}.
\]

It is isomorphic to the direct sum of Koszul complexes defined by \( (L^{(\alpha)}[N^{-1}], \tau(\alpha_i + \beta n_i) I d + N_i - n_i N)_{i \in [1, n]} \). The complex \( \Omega(L^{(\alpha)}, \tau(\beta n_i + \alpha_i) I d + N_i) \) is acyclic unless \( (n_i \beta + \alpha_i) \in \mathbb{N} \) for all \( i \in M \), hence \( \Psi_{\mathcal{L}}^\beta (L) \) is acyclic but for a finite number of \( \beta \) such that \( e(\beta) \) is an eigenvalue of the monodromy action. The proof of Deligne’s result [11] reduces to:

The fiber at zero in \( D^{n+k} \) of \( \Psi_f (\mathcal{L}) \) (resp. \( \Psi_f^u (\mathcal{L}) \)) is quasi-isomorphic to a (finite ) direct sum of \( \Psi_{\mathcal{L}}^\beta (L)(25) \) (resp. to \( \Psi_0^0 (L) \) for \( \beta = 0 \))

\[
(26) \quad \Psi_f (\mathcal{L})_0 \simeq \bigoplus_{\beta \in \mathbb{C}} \Psi_{\mathcal{L}}^\beta, \quad \Psi_f^u (\mathcal{L})_0 \simeq \Psi_0^0 \mathcal{L}
\]

### 3.1 The weight and Hodge filtrations on \( \Psi_0^0 \mathcal{L} \)

We consider again a nilpotent orbit \( L \). To describe the weight in terms of the filtrations \( (\Omega^* L, \mathcal{W}, F) \) associated to \( L \), we need to use the constant complex with index \( s \in S(M) \), \( \Psi_0^0 \mathcal{L}(s.) = \Psi_0^0 \mathcal{L} \) and introduce the complex

\[
(27) \quad (\Psi_0^0 (L))_{S(M)} = s(\Psi_0^0 (L(s.)))_{s \in S(M)}
\]

which can be viewed also as \( s(\Omega^* L[p], \eta)_{p \leq 0} \), then we define on it the weight filtration

\[
(28) \quad \mathcal{W}_r (\Psi_0^0 (L))_{S(M)} = s(\mathcal{W}_{r+2p-1} \Omega^* L[p], \eta)_{p \leq 0}, \quad F^r (\Psi_0^0 (L))_{S(M)} = s(F^{r+p} \Omega^* L[p], \eta)_{p \leq 0}.
\]

Monodromy.
The logarithm $\mathcal{N}$ of the monodromy is defined by an endomorphism $\nu$ of the complex $\Psi^0(L)_{S(M)}$, given by the formula

$$\forall a_i = \sum_{p \leq 0} a_p \in (\Psi^0 L)_{S(M)}, (\nu(a_i))_p = a_{p-1} \forall p \leq 0$$

such that $\nu(W_r) \subset W_{r-2}$ and $\nu(F^r) \subset F^{r-1}$.

**Decomposition of $Gr^W_r$**

The morphism $\eta$ induces a morphism denoted also by $\eta : C^{KM}_r L \to C^{KM}_{r+2} L[1]$ so that we can define a double complex and the associated simple complex

$$\Psi^{KM}_r L = \{C^{KM}_{r+2p-1} L[p], \eta[p]_{p \leq 0}, \Psi^K_r L = \Psi^{KK} r L$$

We will see soon that this complex decomposes into a direct sum.

**Lemma:** There exists natural injections of $\Psi^{KM}_r L$ into $Gr^W_r (\Psi^0 L)_{S(M)}$ and a decomposition

$$Gr^W_r (\Psi^0 L)_{S(M)} \simeq \oplus_{K \in M} \Psi^{KM}_r L$$

**Proof:** By the spectral sequence of a double complex, it is enough to check the decomposition on the columns where the proof reduces to the decomposition in the open case.

**Theorem:** The weight filtration (28) coincides with $W(N)$ defined by the logarithm of the monodromy in the abelian category of perverse sheaves.

The proof in two steps reduces to the lemma and the proposition below.

**Lemma:** The following statements are equivalent

i) For all $i \geq 1$, $\nu^i : Gr^W_i (\Psi^0 L)_{S(M)} \simeq Gr^W_i (\Psi^0 L)_{S(M)}$.

ii) For all $i \geq 1$, $Gr^W_i \ker \nu^i = s(Gr^W_{i+2p-1} \Omega^* L[p], \eta)_{-i < p \leq i} \simeq 0$.

**Proof:** The morphism $\nu^i$ on $(\Psi^0 L)_{S(M)}$ is surjective and its kernel is sum of the columns of index $-i < p \leq 0$.

**Remark:** It may be interesting for the reader to check the statement on the example of a line with $f$ equivalent at $0$ to $z^n$ on the fiber of $(\Psi^0 L)$ at the point $0$ for $L = \mathbb{C}$ and $N = 0$, where the similarity and the differences with Steenbrink’s construction appears already.

**Proposition:** For all $i \geq 1$, $Gr^W_i \ker \nu^i = s(Gr^W_{i+2p-1} \Omega^* L[p], \eta)_{-i < p \leq i} \simeq 0$.

**Proof:** Let $\nu^{KM}_i := s[C^{KM}_{i+2p-1} L[p], \eta]_{-i < p \leq i}$, then by the decomposition theorem we have:

$Gr^W_i \ker \nu^i \cong \oplus_{K \in M} \nu^{KM}_i$. Denotes $\nu^K_i$ by $\nu^{KM}_i$, then we can easily check that $\nu^{KM}_i$ is the intermediate extension of $\nu^K_i$ and is quasi-isomorphic to zero if $\nu^K_i \cong 0$, so we reduce the proof to

**Lemma:** For all $i \geq 1$, $\nu^K_i := s[C^{K}_{i+2p-1} L[p], \eta]_{-i < p \leq i} \cong 0$

**Proof:** In order to give a proof by induction for $i$ assuming the result for $i = -2$, we write $\nu^K_i$ as:

$s[C^{K}_{-(i-1)} L[-(i - 1)], s[C^{K}_{i+2p-1} L[p], \eta]_{-i < p \leq i} \cong 0$

We know that $C^{K}_{-(i-1)} L || \ K \ | -1 \] \simeq Gr^W_{K, -(i-1)}[(\cap_{i \in K \ker N^i} : L \to L] \simeq$

$$\oplus_{(m_1, \ldots, m_n) \in T(r)} Gr^W_{m_1} \cdots Gr^W_{m_2} \cdots Gr^W_{m_1}[(\cap_{i \in K \ker N^i} : L \to L]$$

and $C^{K}_{(i-1)} L || \ K \ | -(i-1) \] \simeq Gr^W_{K, -(i-1)}[L/(\Sigma_{i \in K \ker N^i} L)]$

$$\simeq \oplus_{(m_1, \ldots, m_n) \in T(r)} Gr^W_{m_n-2} \cdots Gr^W_{m_2-2} \cdots Gr^W_{m_1-2} \cdots Gr^W_{m_1-2} \cdots Gr^W_{m_1-2} L/(\Sigma_{i \in K \ker N^i} L]$.$
Given a nilpotent orbit \((L, N_i)\), we denote in general the primitive part of \((Gr_r^{W(N)}L)\) by \((Gr_r^{W(N)}L)^0\), then we have the following isomorphisms:

\[ Gr_r^{W(N)}(L/NL) \simeq (Gr_r^{W(N)}L)^0 \overset{\text{ker}}{\rightarrow} (Gr_r^{W(N)}ker N), \]

so we can deduce in general:

\[ N_1^{m_1} \cdots N_n^{m_n} : Gr_{m_1}^{W(N)} \cdots Gr_{m_n}^{W(N)} | L/(\bigwedge_{i \in K} L) \simeq Gr_{m_1}^{W(N)} \cdots Gr_{m_n}^{W(N)} \cap \bigwedge_{i \in K} ker N_i \]

the sum over \(\{ (m_1 \geq 0, \cdots, m_n \geq 0) : (\bigwedge_{i \in K} m_i = i - 1 - 1 | K | \text{ induces an isomorphism} : \gamma : Gr_{i-1-1|K}|L/(\bigwedge_{i \in K} N_i) \rightarrow Gr_{i-1-1|K}|((\bigwedge_{i \in K} ker N_i : L \rightarrow L) \]

since \(Gr_{-(i-1)+1|K}|\bigwedge_{i \in K} ker N_i : L \rightarrow L\) is isomorphic to

\[ \bigoplus_{\{ (m_1 \leq 0, \cdots, m_n \leq 0) : (\bigwedge_{i \in K} m_i = |K|-i+1 \cdots \oplus Gr_{m_1}^{W(N)} \cdots Gr_{m_n}^{W(N)} \cdots Gr_{m_1}^{W(N)} \}

Then \(\gamma\) induces a quasi-isomorphism from

\[ C^K_{i-1|K}|L | K | \cong Gr_{i-1-1|K}|L/(\bigwedge_{i \in K} N_i)|L \cong Gr_{i-1-1|K}|((L/(N_1L)/N_2(L/N_1L)) \]

to \(C^K_{i-1|K}|L | K | -1\).

A diagram chasing shows that \(\nu^i\) is in fact a cone over \(\gamma^{-1}\), hence zero, which establishes the lemma and the proposition.

Corollary: The grading part of \((\Psi^0L)_{S(M)}\) is non zero for only a finite number of indices for which it reduces to a double complex of finite terms. More precisely, let \(i_0\) be an integer large enough to have \(Gr_j^W\Omega^*L = 0\) for all \(j > i_0\), then for a given \(i \geq 1\):

\[ Gr_i^W(\Psi^0L)_{S(M)} \cong s(Gr_{i+2p-1}W_{\Omega^*L[p], \eta}_{p \leq -i}) \]

where only a finite number of \(p\) such that \(-i_0 \leq i + 2p - 1 \leq -i - 1\) are non zero in the right term. For \(p \neq 1\) we use the isomorphism \(\nu^{-1}\). In particular, \(Gr_i^W(\Psi^0L)_{S(M)} \cong 0\) for all \(i\) such that \(|i| \geq i_0\). We have a direct sum of intermediate extensions (up to shift in degrees) of \(VHS\) of weight of \(m + 1\).

Proof: Suppose \(i > 0\), then \(Gr_i^W(\Psi^0L)_{S(M)} = s(Gr_{i+2p-1}W_{\Omega^*L[p], \eta}_{p \leq 0})\) is the cone over

\[ \eta : s(Gr_{i+2p-1}W_{\Omega^*L[p], \eta}_{p \leq 0}) \rightarrow s(Gr_{i+2p-1}W_{\Omega^*L[p], \eta}_{p \leq -i}) \]

where the first complex is \(Gr_i^Wker \nu^i\) hence quasi-isomorphic to zero, then the corollary follows.

Remark: i) This corollary, shows that the weight filtration behaves like a finite one, so that we can apply in the proper case the results on mixed Hodge complex where the weight filtration is supposed to be finite.

ii) In Steenbrink’s case that is \(L = \mathbb{C}\), \(s(W_{p-1}\Omega^*L[p], \eta)_{-1 \leq p \leq 0}\) is a subcomplex quasi-isomorphic to \((\Psi^0L)_{S(M)}\). For a general \(L\), it is not a complex, nevertheless the graded part behaves like if we restrict to such object.

iii) Dually, we could define \((\Psi^0L)_{S(M)}\) as \(i^*_s s(\Omega^*L[p], \eta)_{p \geq 0}[1]\), with the filtrations

\[ W_r = s(W_{r+2p+1}\Omega^*L[p], \eta)_{p \geq 0}[1], \quad F^r = s(F^{r+p+1}\Omega^*L[p], \eta)_{p \geq 0}[1] \]

then the above results show that the two definitions give quasi-isomorphic complexes and the formula for \(Gr^W\) behaves like if we could use the quotient by \(W_{p}\Omega^*L\) in each column \(p\).

We will see later that we can take the quotient with the subcomplex generated by \(ICL\) for \(p = 0\) and then use the induced filtrations on the quotient.

Corollary (decomposition): Let \(I(p) = \{ p \leq 0, -i_0 \leq i + 2p - 1 \leq -i - 1\}\), then:

\[ Gr_i^W(\Psi^0L)_{S(M)} = s(Gr_{i+2p-1}W_{\Omega^*L[p], \eta})_{p \in I(p)} = \bigoplus_{p \in I(p)} Gr_{i+2p-1}W_{\Omega^*L[p]} \]

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Proof: It follows from the remark that \( G^W_t(\Psi^0L)_{S(M)} \) can be computed for a finite number of columns such that \( r = i + 2p - 1 \leq p - 1 < 0 \) is negative and where each term is a direct sum of \( C^{LM}_r \), intermediate extension of \( C^{LM}_r \) whose cohomology is concentrated in degree \( |K| - 1 \), hence the map \( \eta \) is zero and we get a direct sum instead of a double complex.

3.2 The global weighted complex \( (\Psi^y_f(L), W, F) \)

Returning to the global situation, we need to define the Hodge filtration on \( \Psi_f(L_X) \). First \( F \) extends to the logarithmic complex by the formula: \( F^p(\Omega^q_X(LogY) \otimes L_X) = s(\Omega^q_X(LogY) \otimes F^{p-q}(L_X), \nabla_X)_{p \leq 0} \), then \( F \) extends to \( (\Psi_f(L_X)) \) via the formula
\[
F^r(iY^*s(\Omega^r_X(LogY) \otimes L_X[i], \eta)|_{i \leq 0}) = iY^*s(F^{r+p+1}(\Omega^r_X(LogY) \otimes L_X[i], \eta)|_{i \leq 0})
\]

The definition of the global weight filtration reduces to the local construction at a point \( y \in Y^*_M \), using the quasi-isomorphism \( (\Psi_f(L^{(a.)}))_y \simeq \oplus \beta \Psi^\beta(L^{\ell(a.)}) \).

We suppose again \( L \) unipotent and define as previously \( (\Psi^y_f(L)_{S(M)}) := s(\Psi^{(a.)}_f(L^s), \eta)|_{S(M)} \) which can be viewed also as \( s(\Omega^r[L[p], \eta]_{p \leq 0}) \), then we define on it the weight filtration
\[
W_r(\Psi^y_f(L)_{S(M)}) = iY^*s(W_{r+2p-1}(\Omega^s[L[p], \eta])_{p \leq 0}), \quad F^r(\Psi^y_f(L)_{S(M)}) = iY^*s(F^{r+p+1}(\Omega^s[L[p], \eta])_{p \leq 0})
\]
The logarithm of the monodromy \( N \) is defined on this complex as in the local case. The filtration \( W(N) \) is defined on \( (\Psi^y_f(L)_{S(M)}) \) in the abelian category of perverse sheaves.

Theorem: Suppose \( L \) underlies a unipotent variation of polarised Hodge structures of weight \( m \), then the graded part of the weight filtration (30) of the complex
\[
(\Psi^y_f(L^s)_X, W[m], F)
\]
decomposes into a direct sum of intermediate extension of VHS; moreover we have \( W(N) = W \).

The proof of this theorem reduces by definition to show that \( (Gr^W_r W[m], F) \) decomposes which result can be reduced to the local case where it has been checked in the above corollaries.

Remark: We could as well define the complex \( (\Psi^0L)_{S(M)} \) by summing over \( p \geq 0 \):
\[
(\Psi^0L)_{S(M)} = iY^*s(s(\Omega^r_X(LogY) \otimes L_X[p], \eta]|_{p \geq 0}, [1])
\]

By the above remarks the two definitions give quasi-isomorphic complexes.

3.3 The global weighted complex of \( (\Psi_f(L), W, F) \)

Let \( y \in Y^*_M \), we deduce from the isomorphism
\[
(\Psi_f(L^{(a.)}))_y \simeq \oplus \beta \Psi^\beta(L^{\ell(a.)})
\]
the global weight filtration in the abelian category of perverse sheaves on Deligne’s extension \( (\ell(a.) \otimes f^{-1}V\beta)_X \) and the associated combinatorial logarithmic complex \( \Omega^r(L^{\ell(a.)} \otimes f^{-1}V\beta) \) where we define the global weight filtration in the abelian category of perverse sheaves at points \( y \) such that \( L^{\ell(a.)} \otimes f^{-1}V\beta \) is unipotent since otherwise it is acyclic near \( y \) and doesn’t contribute to cohomology.

Finally we can define the combinatorial logarithmic filtered complex as:
\[
(\Psi_f(L), W) = \oplus (a, \beta)(\Psi^y_f(L^{\ell(a.)} \otimes f^{-1}V\beta), W)
\]
The Hodge filtration \( F \) extends to the logarithmic complex and to \( \Psi_f(L_X) \).
Theorem: Suppose $\mathcal{L}$ underlies a variation of polarised Hodge structures of weight $m$, then the complex

$$(\Psi_f(\mathcal{L}_X), \mathcal{W}[m], F)$$

decomposes into a direct sum of intermediate extension of VHS; moreover we have $W(N) = \mathcal{W}$ where $N$ is the logarithm of the unipotent part of the monodromy $T^u$.

II. The weight filtration after M. Kashiwara and M. Saito

Local situation. We give in this subsection Kashiwara and Saito’s constructions and indications on the proofs of the decomposition and the purity results for $\Psi^*_f(\mathcal{L})$ in order to compare the two constructions. In the reference this result is embedded in the language and theory of Hodge modules, a theory adapted for general pushforward results but not necessary at this stage.

Given $\alpha_i \in [0,1]$ for $i \in [1,n]$ (or equivalently a section $\tau$ with value in $[0,1]$), we consider the polynomial ring $\mathbb{C}[N]$ in one variable (resp. the field $\mathbb{C}[N,N^{-1}]$) and the module $L[N] = L \otimes_{\mathbb{C}} \mathbb{C}[N]$ (resp. $L[N,N^{-1}]$) endowed with commuting endomorphisms $(\alpha_i \text{Id} + N_i) \otimes \text{Id}$ where $N_i$ is nilpotent, denoted also by $\alpha_i \text{Id} + N_i$, and multiplication by $N$ denoted also by $N$. For each family of numbers $n_i > 0$, for $i \in [1,n]$, we consider the endomorphisms $A_i = \alpha_i \text{Id} + N_i - n_iN$ on $L[N]$ (resp. $L[N,N^{-1}]$). When $\alpha_i \neq 0$, $A_i$ is invertible on $L[N]$ and when $\alpha_i = 0$, the inverse of the endomorphisms $A_i$ are defined on $L[N, N^{-1}]$ and equal to

$$A_i^{-1} = -\sum_{j \geq 0} (N_i)^j / (n_iN)^{j+1}$$

where the sum is finite since $N_i$ is nilpotent for all $i$. In particular $A_i$ and $A_J = \Pi_{i \in J} A_i$, $J \subset [1,n]$, are injective on $L[N]$ so that we can deduce

Lemma. Given $(L, \alpha_i \text{Id} + N_i)_{i \in [1,n]}$, we let $I(\alpha.) = \{ i \in [1,n] : \alpha_i = 0 \}$
i) The complex $\Omega(L[N,N^{-1}], A_i = \alpha_i \text{Id} + N_i - n_iN, i \in [1,n])$ is acyclic.
ii) The following complexes are isomorphic

$$\Omega(L[N^{-1}], A.) \xrightarrow{\sim} \Omega(L[N], A.)[1]$$

iii) The complex

$$(33)\quad IC(L[N], A.) = s(\text{Im} A_{J \cap I(\alpha.)}, J \subset [1,n]) \simeq 0, \quad (\text{Im} A_{J \cap I(\alpha.)} = \text{Im} A_J)$$

is an acyclic sub-complex of the Koszul complex $\Omega(L[N], A.)$.
iv) Let $\Psi_f(L) := L[N]/\text{Im} A_{J \cap I(\alpha.)}$ and $\Psi^0 L = s(\Psi_f(L), J \subset [1,n], (A_i)_{i \in [1,n]}[1])$, be associated to the simplicial complex with differential induced by $A_i : \Psi_{f-1}(L) \rightarrow \Psi_f(L)$, then we have the following isomorphism

$$(34)\quad \Omega(L[N], A.) \xrightarrow{\prod} \Psi^0 L = s(\Psi_f(L), J \subset [1,n], A.), J \subset [1,n][1]$$

We give the statement for $\Psi^\beta(L^{(\alpha.)})$ in general

Proposition: Given $(\alpha.) = (\alpha_j)_{j \in [1,n]}$ and $\beta$, we consider on $L^{(\alpha.)}$ the endomorphisms $A_i = (\tau(\alpha_i + \beta n_i) \text{Id} + N_i - n_iN)$ for $i \in [1,n]$ then we have the isomorphisms:

$$\Psi^\beta(L^{(\alpha.)}) = \Omega(L^{(\alpha.)}[N^{-1}], A.) \simeq \Omega(L^{(\alpha.)}[N], A.)[1].$$

Let $\text{Im} A_J = \text{Im} (A_{J \cap I(\tau(\alpha_i + \beta n_i)})$ in $L^{(\alpha.)}$ denotes the image of the composition $A_J = \Pi_{j \in J} A_j$ then this Koszul complex is isomorphic to

$$(35)\quad \Psi^\beta(L^{(\alpha.)}) = s((L^{(\alpha.)}[N]/\text{Im} A_{J \cap I(\tau(\alpha_i + \beta n_i))}, A.), J \subset [1,n][1].$$
Let \( S(\alpha) = \{ \gamma \in \mathbb{C} : \forall j \in M, \alpha_j + n_j \gamma \in \mathbb{N} \} \). Only for \( \beta \in S(\alpha) \) the complex is not acyclic.

Remark i) The importance of the introduction of \( \Psi \) to the perverse sheaf \( \Psi^0(L) \) is that they are canonically associated to the perverse sheaf \( \Psi^0(L) \), so that the construction of the weight filtration reduce to its construction on these vector spaces. It is more precise to work on these vector spaces then on the cohomology of the perverse sheaf, the relation being a kind of spectral sequence.

ii) We can give now a proof of the isomorphism (20) of the proposition in this paragraph. Recall that \( \Psi_J L = L[N]/\text{Im}A_J \) and we have \( \text{Coker}N/\Psi_J L \simeq \text{Coker}N - \text{Coker}J - L \) since \( A_i = N_i - n_i N \) is equal to \( N_i \) modulo \( N \), so that we have locally at \( y \in Y^*_M \) the isomorphisms

\[
(j_* \mathcal{L}/j_* \mathcal{L})_y \simeq s(\text{Coker}N/J)/j_{[1,n]} \simeq \text{Coker}N/s(\Psi_J L)_{j[1,n]} \simeq \text{Coker}N/\Psi^J \mathcal{L}[-1]
\]

which establishes (20).

iii) In general, the graded part of the cokernel is the primitive part \( P_k(N) \) for all \( k \geq 0 \):

\[
\text{Gr}_k^W(N)/(\Psi_J N/\Psi_J L) \simeq P_k(N).
\]

The filtration \( W(N) \) on \( \Psi_J L \) defines a filtration by sub-complexes of \( \Psi^0L \) and corresponds to the filtration \( W(N) \) of \( \Psi^J \mathcal{L} \).

Now in order to study the weight filtration we need to consider this complex as a perverse sheaf in the corresponding abelian category. That is why we recall here basic facts on this category needed to understand the construction.

The category of perverse sheaves \( \mathcal{L} \) on \( X \) with respect to the natural stratification \( Y^*_M \) defined by \( Y \) (i.e., such that for each \( M \subseteq I \), the cohomology of \( \mathcal{L} / Y_M^* \) is locally constant), are described locally at a point \( y \) considered as the center of a polydisc \( (D^*)^M \), from a topological viewpoint, by the following combinatorial construction in [25, p 996] (see also [16], [2]).

The category \( \mathcal{P} \) of perverse sheaves \( \mathcal{L} \) on \( (D^*)^M \), with respect to its NCD stratification is equivalent to the abelian category defined as follows:

i) A family of vector spaces \( L_A \) for \( A \subseteq M \),

ii) A family of morphisms

\[
f_{AB}: L_B \to L_A \text{ and } h_{BA}: L_A \to L_B \text{ for } B \subseteq A \subseteq I \text{ such that :}
\]

\[
f_{AB} \circ f_{BC} = f_{AC} \quad h_{CB} \circ h_{BA} = h_{CA} \text{ for } C \subseteq B \subseteq A
\]

\[
f_{AA} = h_{AA} = \text{id} \quad h_{A,A\cup B} \circ f_{A\cup B,B} = f_{A,A\cap B} \circ h_{A,A\cap B,B} \text{ for all } A,B
\]

and if \( A \supset B, |A| = |B| + 1 \), then \( 1 - h_{BA}f_{AB} \) is invertible.

Minimal extensions

We will need the following description for \( A \subseteq M \) of the category \( \mathcal{M}_A \) of the minimal extensions of a locally constant sheaf \( \mathcal{L} \) on \( X^*_A \): in terms of the family of vector spaces \( L_B \) for \( B \subseteq M \); it is equivalent to \( L_B = 0 \) for \( A \nsubseteq B \), and \( f_{BA} \) is surjective and \( g_{AB} \) is injective for \( A \subseteq B \). We denote by \( \mathcal{M} \) the objects isomorphic to a direct sum of objects in \( \bigcup A \mathcal{M}_A \).

The category \( \mathcal{M} \) of sums of minimal extensions

A result of Kashiwara states [25, p 997]

A perverse sheaf \( \mathcal{L} \in \mathcal{P} \) is a direct sum of minimal extensions (in \( \mathcal{M} \) ) if and only if

\[
\forall A, B \subseteq M, \quad L_A \simeq \text{Im}f_{AB} \oplus \text{Ker}g_{BA}
\]

Moreover, it is enough to consider \( |A| = |B| + 1 \).

The above condition is equivalent to the isomorphism:

\[
\oplus_{B \subseteq A} f_{AB}(P_B(\mathcal{L})) \sim L_A
\]

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where $P_B(L) = \cap_{C \subseteq B} \text{Ker} g_{CB}$, then moreover $g_{BA} : f_{AB}(P_B(L)) \to P_B(L)$ is injective for $B \subset A$.

**Description of the weight filtration in the category of perverse sheaves.** The family $\Psi_j^\beta(L^{(\alpha)}) = L^{(\alpha)}[N]/\text{Im} A_{J,j}(\tau_{(\alpha_+\beta_n)})$ for $J \subset M, J \neq \emptyset$ gives precisely the description of $\Psi(\Omega^{(\alpha)})$ as a perverse sheaf, where for $i \in J$, the morphisms $f_{J-i} = A_i : \Psi_j^\beta(L^{(\alpha)}) \to \Psi_j^\beta(L^{(\alpha)})$ and $g_{J-i} = p_i : \Psi_j^\beta(L^{(\alpha)}) \to \Psi_j^\beta(L^{(\alpha)})$ is the canonical projection. The product by $N$ induces on each $\Psi_j^\beta(L^{(\alpha)})$ a nilpotent endomorphism denoted also by $N$ which commutes with $A_i$ and $p_i$, hence these morphisms are compatible with $W(N)$: they send $W_{r-1}(N)$ into itself (it is enough to show that for $b \in \Psi_{J-i}(L^{(\alpha)})$, if $N^s(b) = 0$ for $s \geq r$, $N^s(A_i(b)) = A_i(N^s(b) = 0$ (resp.for $p_i$)).

For each integer $r$, let $Gr_r^{W(N)}(\Psi_j^\beta(L^{(\alpha)}), p^r_i, A^r_i$ denotes the corresponding perverse graded objects, then we define

$$K^r_i = \text{Ker } p^r_i : Gr_r^{W(N)}(\Psi_j^\beta(L^{(\alpha)})) \to Gr_r^{W(N)}(\Psi_j^\beta(L^{(\alpha)}))$$

in particular $\forall i \in J, K^r_i \subset \text{Ker} N_i \subset Gr_r^{W(N)}(\Psi_j^\beta(L^{(\alpha)}))$. The aim of the next part is to deduce the decomposition property (37) via the proof of (36) in presence of a polarised Hodge filtration.

First we give a global setting of the problem.

**3.4 The global weighted complex of nearby cycles** $(\Psi_f(L), W(N))$ In this subsection, we define the weight filtration abstractly without going back to an explicit formula as used on the combinatorial logarithmic complex. The filtration $W(N)$ on each $\Psi(\Omega^{(\alpha)})$ defines a filtration by sub-complexes on $\oplus_{\alpha} \Psi(\Omega^{(\alpha)})$ and corresponds via (32) to the filtration $W(N)$ of $\Psi_f(L)_y$ in the abelian category of perverse sheaves where $N = -1/2i\pi \text{Log} T^u$.

Consider Deligne’s extension $(L^{(\alpha)} \otimes f^{-1}V_\beta)_X$ and the associated logarithmic complex $i_Y^* \mu (\Omega^\alpha_X(\text{Log} Y) \otimes (\mathcal{L}^{(\alpha)} \otimes f^{-1}V_\beta)_X[p], \eta)_{p \geq 0}$. There exists a global acyclic sub-complex $IC((\mathcal{L}^{(\alpha)} \otimes f^{-1}V_\beta)_X[N])$ inducing at each fiber at the point $y$ the complex $IC(L^{(\alpha)}[N], A_i = (\tau(\beta n_i + \alpha_i) + N_i - n_i N)).$ We define the weight filtration $W(N)$ on the quotient complex

$$\Psi^\beta_j((\mathcal{L}^{(\alpha)} \otimes f^{-1}V_\beta)_X) = \{s(\Omega^\alpha_X(\text{Log} Y) \otimes (\mathcal{L}^{(\alpha)} \otimes f^{-1}V_\beta)_X[p], \eta)_{p \geq 0}/IC(L^{(\alpha)} \otimes f^{-1}V_\beta)_X[N])\}_1$$

as the filtration inducing $W(N)$ at each fiber $\Psi^\beta_j(L^{(\alpha)})$ at points of $Y$. Finally we can define the logarithmic filtered complex as:

$$\Psi_f(L, W(N)) = \oplus_{(\alpha, \beta)}(\Psi_f^\mu((\mathcal{L}^{(\alpha)} \otimes f^{-1}V_\beta)_X, W(N))$$

The filtration $F$ extends to $(\Psi_f(L), W(N))$ via its extension to $\Omega^\alpha_X(\text{Log} Y) \otimes L_X[N][1]$ by the formula

$$F^p(i_Y^* s(\Omega^\alpha_X(\text{Log} Y) \otimes L_X[i], \eta))_{i \geq 0}[1] = i_Y^* s(F^{p+1}(\Omega^\alpha_X(\text{Log} Y) \otimes L_X[i], \eta))_{i \geq 0}[1]$$

$$= i_Y^* s((s(\Omega^\alpha_X(\text{Log} Y) \otimes F^{p+1}(L_X[q \geq 0][i], \eta))_{i \geq 0}[1].$$

**Theorem:** Suppose $L$ underlies a variation of polarised Hodge structures of weight $m$, then graded part of the weight on the complex (39) with the filtration $F$ defined above

$$\Psi_f(L, W(N)[m], F)$$

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decomposes into intermediate extensions of $VHS$.

The proof of this theorem reduces by definition to show that $(Gr^W_a)^{(N)[m]}_r, F)$ decomposes. This can be checked locally via (36) and (37). That is we need to use the following decomposition theorem based on results due to Kashiwara [25] in characteristic zero and proved in [2] in the language of purity in positive characteristic.

**Theorem (decomposition) (Kashiwara - Saito):** For each integer $a$, $Gr^W_a(L^{e(\alpha)})_y \simeq Gr^W_a(L^{e(\alpha)})_y \simeq Gr^W_a(L^{e(\alpha)})_y$ is isomorphic to a direct sum of fibers at $y$ of various intermediate extension of variations of polarised Hodge structures. Precisely

\[
Gr^W_a(L^{e(\alpha)})_y \simeq \bigoplus_{J \subseteq M} IC((K^+_j(L^{e(\alpha)}), N, i \in M - J)
\]

where $K^+_j$, defined by (38), is a pure Hodge structure of weight $a + m$ with the induced Hodge filtration $F$.

i) Elements of Kashiwara’s proof [30, prop. 3.19, and Appendix]. We will write $L$ for $L^{e(\alpha)}$ and associate to $(L, F, P, N, i \in M = [1, n])$ the module $L[N]$ where $N$ is a polynomial variable, endowed with two filtrations as follows. Consider $W(L) = W(\Sigma_{i \in M} N_i)[m]$ and $F$ on $L$, then define

\[
W_k(L[N]) = \Sigma_j W_{k+2j} \otimes N^j, F^p(L[N]) = \Sigma_j F^{p+j} L \otimes N^j
\]

Since the endomorphisms $A_i = N_i - n_i N$ shift $W$ by $-2$ and $F$ by $-1$, the two filtrations induce a $MHS$ on the cokernel $\Psi_L = L[N]/\text{Im} A_J$ for $J \subseteq M$. We have an isomorphism compatible with the filtrations

\[
(\bigoplus_{j \leq l-1} L \otimes N^j, W, F) \simeq (\Psi_L, W, F)
\]

obtained via the composition of the natural embedding in $L[N]$ with the projection on $\Psi_L$, where $W$ and $F$ are defined on the left term as in the formula (42) above. In fact the relation:

\[
N^l = \Sigma_{j \geq l} (-1)^j \sigma_j N^{l-j}, \quad \text{ where } l = |J| \quad \text{and } \sigma_j \text{ is the } j^{th} \text{elementary symmetric function of } \Sigma_{i \in J} N_i, \quad \text{on the quotient of the right term leads to the definition of the action of } N \text{ on the left term by the formula:}
\]

\[
N(a \otimes N^{l-1}) = \Sigma_{1 \leq j \leq l} (-1)^{j+1} \sigma_j ((N_i/n_i), i \in J) (a) \otimes N^{l-j}.
\]

In order to define a polarisation we introduce a product $P_J$ on $\Psi_L$ (L) as follows

\[
P_J(aN^i, bN^j) = P(a, (-1)^i \text{ Res}(A^{-1}_i(b \otimes N^{i+j})))
\]

where $A^{-1}_i$ is defined on $L[N, N^{-1}]$, $N$ is considered as a variable $x$ and the residue $\text{Res}$ is equal to the coefficient of $1/N$ in the fraction in $N$. This formula shows directly that the product is well defined on $Coker A_J$; in fact, $P_J(aN^i, A_J(c) = P(a, (-1)^i \text{ Res}(c \otimes N^i)) = 0$ since the residue is zero. Using an explicit expression of $A^{-1}_i$, we find $P_J(aN^p, bN^q) = (-1)^q P(a, \Sigma_{a_i}(\Pi_{i}(N^{a_i}(b)/n_i^{a_i+1}))$ where $a_i \geq 0$ and $\Sigma_i a_i = i + j - l + 1$. In particular

\[
P_J(a, bN^r) = (1/\Pi_{i} n_i) P(a, b) \quad \text{if } r = l - 1, \quad \text{and zero otherwise}
\]

\[
P_J(aN^i, bN^j) = (-1)^j P_J(a, bN^{i+j}).
\]

In [30], the following result is attributed to Kashiwara

**Theorem :** With the previous notations, namely $W$ and $F$

\[
\Psi_L(L) = (L[N]/\text{Im} A_J, N_1, \ldots, N_n, N; W, F, P_J)
\]
underlies a polarised nilpotent orbit of weight $m + 1 - |J|$, that is: the weight filtration $W(N + \Sigma_{i \in J} N_i)[m + 1 - |J|] = W$ underlies the weight of a MHS on $\Psi_j(L)$ with the Hodge filtration $F$.

ii) (see M. Saito [29,5.2.15, 5.2.14], [30,3.20.4]). The induced morphisms $N, N_i$ and $A_i$ shift $W$ by $-2$ and $F$ by $-1$. Since $W(N + \Sigma_{i \in J} N_i)$ is the weight filtration of the endomorphism $\Sigma_{i \in J} N_i$ relative to $W(N)$ that is for all $\Psi_j(L)$:

$$Gr_j^{W(N + \Sigma_{i \in J} N_i)} Gr_r^{W(N)(\Sigma_{i \in J} N_i)^J} \xrightarrow{\Gamma^W_{j-r}} Gr_r^{W(N + \Sigma_{i \in J} N_i)} Gr_r^{W(N)}$$

we have:

$$Gr_j^{W(N + \Sigma_{i \in J} N_i)} Gr_r^{W(N)} \simeq Gr_j^{W(\Sigma_{i \in J} N_i)} Gr_r^{W(N)} \simeq Gr_j^{W(\Sigma_{i \in J} A_i)} Gr_r^{W(N)}$$

Now we may consider the orbit with only two endomorphisms ($\Psi_j(L), N_i, N, F = F(N_i)$) ($F$ is the limit along the axis $Y_i$), then we deduce commutative diagrams for $j$ varying in an interval of $\mathbf{Z}$ symmetric with center 0 with at left $HS$ of weight $n + j$ where $n = m + a - |J|$ and to the right $n + j - 1$

$$\begin{align*}
Gr_j^{W(N_i)} Gr_r^{W(N)} \Psi_{j-i} L & \xrightarrow{A_i} Gr_j^{W(N_i)} Gr_a^{W(N)} \Psi_j L(-1) \\
\downarrow N_i & \downarrow N_i \\
Gr_j^{W(N_i)} Gr_r^{W(N)} \Psi_{j-i} L(-1) & \xrightarrow{A_i} Gr_j^{W(N_i)} Gr_r^{W(N)} \Psi_j L(-2)
\end{align*}$$

moreover we have: $P_f(A_i u, v) = P_{j-i}(u, p_i v)$ for all $u \in \Psi_{j-i} L$ and $v \in \Psi_j L$

In this situation, a result of M. Saito [MI,5.2.15] applies and shows

Proposition: For all $J \subset I$ and $i \in J$, consider the morphisms

$$Gr_a^{W(N)} \Psi_{j-i} L \xrightarrow{A_i} Gr_a^{W(N)} \Psi_j L(-1) \xrightarrow{p_i} Gr_a^{W(N)} \Psi_{j-i} L(-1)$$

then we have a decomposition

$$Gr_a^{W(N)} \Psi_j L \simeq \text{Im} A_i \oplus \ker p_i$$

compatible with the primitive decomposition. In particular, $p_i$ induces an isomorphism of $\text{Im} A_i$ in $Gr_a^{W(N)} \Psi_j L$ onto $\text{Im} A_i$ in $Gr_a^{W(N)} \Psi_{j-i} L$.

The result is deduced from the sequence in the proposition by taking its graded version $Gr_{j-1}^{W(N_i)}$ for various $j$ as in (45) and using the polarisation of $HS$ induced on, to prove for each $j$,

$$\text{Im} A_i \oplus \ker p_i \simeq Gr_{j-1}^{W(N_i)} Gr_a^{W(N)} \Psi_j L(-1)$$

hence, since $A_i$ and $p_i$ are compatible with the $MHS$ of weight $W(N_i)$, we get:

$$\text{Im} A_i \oplus \ker p_i \simeq Gr_a^{W(N)} \Psi_j L(-1).$$

Now, to finish the proof of the decomposition theorem, it remains to show that $K_j^*$ is pure and polarised in two steps:

Lemma: i) $K_j^* \subset W_0(\Sigma_{i \in J} N_i) Gr_a^{W(N)} \Psi_j L$.

ii) $K_j^* \cap (W_{-1}(\Sigma_{i \in J} N_i) Gr_a^{W(N)} \Psi_j L) = 0$.

Proof. i) the assertion (i) follows from the relation: $\ker (\Sigma_{i \in J} N_i) \subset W_0(\Sigma_{i \in J} N_i) Gr_a^{W(N)} \Psi_j L$.

ii) Suppose $x \in W_{-s}(\Sigma_{i \in J} N_i) Gr_a^{W(N)} \Psi_j L \cap K_j^*$ where $-s \leq -1$, then there exists $y \in W_s(\Sigma_{i \in J} N_i) Gr_a^{W(N)} \Psi_j L = W_s(\Sigma_{i \in J} A_i) Gr_a^{W(N)} \Psi_j L$ such that $x = (\Sigma_{i \in J} A_i)^s(y)$ (by surjectivity of $\Sigma_{i \in J} A_i$ on negative weights) then for each $i$, we have $(N_i)^s(y) \in \text{Im} A_i \mod W_{-s-1}$,
hence $x = \sum_i N_i^a(y)$ is in $(\cap_i \ker p_i) \cap \sum_i \text{Im } A_i = 0 \mod W_{s-1}$, that is $x \in W_{-s-1}(\sum_{i,j \in J} N_i)\text{Gr}_J^{W(N)} \Psi JL$. We deduce (ii) by a descending inductive argument on $-s$.

We deduce from the lemma that $K^j_l$ is pure of weight $a$ which ends the proof of the theorem.

III. Example : Rank one local system $\mathcal{L}$ on $X - Y$.

We apply the above theory to remove the base change in Steenbrink's work. In this case the monodromy of $\mathcal{L}$ around components of $Y$ is of the following form: $\forall i \in I, T_i = \alpha_i \text{Id}, N_i = 0$. For $\beta \in \mathbb{Q} \cap [0, 1], \text{let } \nu_j$ denotes the rank one local system on the punctured disc with monodromy $e^{-2\pi \beta j}, S := \mathcal{L} \otimes f^{-1}V_\beta$ and $S_X$ its Deligne's extension; then we can define the weight filtration $W(\mathcal{N})$ explicitly on the complex

$$\Psi^\beta_j((S_X)_j) := i_j^* s(\Omega_X^*(\text{Log} Y) \otimes S_X)[p], \eta \geq 1$$

First we define $W$ on $\Omega_X^*(\text{Log} Y) \otimes S_X$. Let $I(\beta) := \{i \in I : \alpha_i + \beta n_i \in \mathbb{Z}\}$, $Y(\beta) = \bigcup_{i \in I(\beta)} Y_i$, $C(\beta) = \bigcup_{i \in I - I(\beta)} Y_i$, notice that $S_X$ is locally trivial along $Y(\beta) - C(\beta)$ and its logarithmic complex is acyclic along $C(\beta)$, that is for $j : X - Y \rightarrow X$, we have: $(jS)_x |_{X - Y(\beta)} = (jS)/_{X - Y(\beta)}$. We write $\Omega_X^*(\text{Log} Y) as \Omega_X^*(\text{Log} Y(\beta) \otimes \Omega_X^*(\text{Log} C(\beta))$ and extend the logarithmic weight filtration $W(\mathcal{N})$ along $Y(\beta)$ to the whole complex by

$$W := [W^j(\beta)(\Omega_X^*(\text{Log} Y(\beta))) \otimes \Omega_X^*(\text{Log} C(\beta)) \otimes S_X.$$ Then we have

$$Gr^W_j(\Omega_X^*(\text{Log} Y) \otimes S_X) \simeq (Gr^W_j(\Omega_X^*(\text{Log} Y(\beta)))) \otimes \Omega_X^*(\text{Log} C(\beta)) \otimes S_X \simeq \bigoplus_{J \subset I(\beta), |J| = \alpha_j} \Omega_X^*(\text{Log} (C(\beta) \cap J)) |\eta = 1 \otimes S_Y,$$

with the differential of the induced connection on $S_Y$. 

Locally, let $L$ denotes the general fiber of $S$, then the fiber of the logarithmic complex at a point $y \in X^\alpha$ is isomorphic to the Koszul complex $(\Omega(L, \tau(\alpha_i + \beta n_i) \text{Id}, i \in M) where L_j$ corresponds to $L \otimes \bigwedge_{i \in J} dz_i$. For each $i \in M$, let $(i, \beta) = \{j \in I - I(\beta) : Y_j \cap Y_i \neq \varnothing\}$, then the fiber of $Gr^W_i$ is:

$$Gr^W_i \simeq \bigoplus_{i \in I(\beta)} (\Omega(L, \tau(\alpha_j + \beta n_j), i \in J(\beta))$$

This weight filtration and the Hodge filtration extend to $s(\Omega_X^*(\text{Log} Y) \otimes S_X[p], \eta \geq 1]$ by the formula

$$W_i = \bigoplus_{p \geq 0} W_{i+2p+1}, F^3 = \bigoplus_{p \geq 0} F^{i+p+1}.$$ Here the fiber of the double complex at $y$ is isomorphic to the Koszul complex $(\Omega(L[N], A_i = \tau(\alpha_i + \beta n_i) \text{Id}, i \in M) where A_i is an isomorphism whenever $\tau(\alpha_i + \beta n_i) \neq 0$, that is $i \in I - I(\beta)$. Now we introduce the acyclic subcomplex $\mathcal{K} \simeq \bigoplus_{p \geq 0} W_{p+1}$, whose fiber at $y$ in $(\Omega(L[N], A_i = \tau(\alpha_i + \beta n_i) \text{Id}, i \in M)$ is given as $s(K_J)_{J \subset \mathcal{M}} where K_J = Ima_j = LN[L[N$ whenever $\text{J \cap I(\beta) = J(\beta) = r}, (A_j, \Pi_{i \in J} A_i).$

The quotient complex with induced filtration:

$$\Psi^\beta_j(\mathcal{L}) \cong (i_j^* s(\Omega_X^*(\text{Log} Y) \otimes S_X[p], \eta \geq 1]) / \mathcal{K}, W, F$$

is the bifiltered complex computing $\Psi^\beta_j(\mathcal{L})$. The quotient complex has fiber at $y$:

$$s(\Psi_J(L), A_{i,j} \in M)_{J \subset \mathcal{M}}, \Psi_J(L) = (L[N] / \text{Im } A_j) \simeq \bigoplus_{p \geq 0} L[N]^p.$$ Let $K_p$ denotes the $p$th column of $\mathcal{K}$, then the graded object with respect to $W$ is:

$$Gr^W_i(\Psi^\beta_j(\mathcal{L})) \simeq i_j^* s(Gr^W_{i+2p+1}(\Omega_X^*(\text{Log} Y) \otimes S_X[p]) / K_p, p \geq 1] \simeq$$
Proposition: \( W E_1^{p,q}(\mathcal{L}(\mathcal{J})) = \bigoplus_{i \geq 0, j \geq p} \bigoplus_{i,j} H^{2p+q-2i}(Y_j - C(\beta))^{-p+2i+1}, S_j \) where \( S_j \) is a local system on \( Y_j \) deduced from \( S \) as restriction of Deligne's extension \( S \) and has zero restriction to \( C(\beta) \).

The weight spectral sequence is: \( W E_1^{p,q}(\mathcal{L}(\mathcal{J})) := H^{p+q}(X, Gr^W_p \mathcal{L}(\mathcal{J})) = \bigoplus_{i \geq 0} i_{\geq p} H^{p+q-i}(X, Gr^W_{p+2i+1}(\mathcal{J}; Y, \mathcal{J}^{-p+2i+1} \circ S_j)^{-p+2i+1}), S_j \) where \( S_j \) is a local system on \( Y_j \). Let \( M_j \) be a unipotent \( VMHS \) on \( X = Y \) and \( \mathcal{L}_0 \) its canonical extension, then \( W_0 \) (finite) extends to a filtration by sub-bundles. We say that \( \mathcal{L}_0 \) is a filtration by sub-bundles.

4§. Variation of Mixed Hodge structures

Let \( (L, W_0) \) be a filtered object in an abelian category and \( \mathcal{N} \) a nilpotent endomorphism of \( (L, W_0) \). Deligne [10, (6.1.13)] introduced the notion of relative weight filtration \( W \) of \( N \) with respect to \( W_0 \) on \( L \) and showed that if it exists, it is the unique filtration satisfying for all \( a \in \mathbb{Z}, b \in \mathbb{N} \)

\[ NW_a \subset W_a-2 \text{ and } N^b : Gr^W_{a+b} L \simeq Gr^W_{a-b} L \]

A variation of mixed Hodge structures (VMHS) : \( (L, W_0, F) \) is called good [10, (1.8.15)] if there exists a relative weight filtration \( W \) for the action of the logarithm of the monodromy \( N \). We showed in three notes developed in [13], the existence of a limit relative weight filtration \( W \) for geometric VMHS inducing on \( Gr^W_0 L \) the limit of the VHS on \( (Gr^W_0 L, F) \). Steenbrink and Zucker called an axiomatic VMHS admissible if it is good and satisfy a set of properties all satisfied by the geometric case [25], [34]. In this section we show that the definition of the weight filtration extends to this case without major difficulties using only the ingredients of proofs already introduced in the previous cases.

4.1 Good VMHS.

Let \( V_X = (\mathcal{L}, (\mathcal{L}^Q, W_0), (\mathcal{L}^C, W_0 \otimes \mathbb{C}, F)) \) be a unipotent VMHS on \( X = Y \) and \( \mathcal{L}_X \) its canonical extension, then \( W_0 \) (finite) extends to a filtration by sub-bundles. We say that \( V_X \) is good if the following properties are satisfied:

i) the filtration \( F \) extends to \( \mathcal{L}_X \) as a filtration by sub-bundles for all \( J \subset I \), the relative filtration \( M_J := W(N_J, W_{Y_J}^0) \) exists (it is a filtration by sub-local systems).

ii) The limit filtrations \( M_J \) define a VMHS \( V_{Y_J} \) on \( Y_J \); moreover \( W_{Y_J}^0 \) is a filtration by sub-VMHS such that the induced VMHS on \( Gr^W_0 \mathcal{L}_{Y_J}^Q \) coincides with the limit of the VHS on \( Gr^W_0 \mathcal{L}_{Y_J}^Q \). \( V_{Y_J} \) is called the limit of \( V_X \) on \( Y_J \).

iv) Compatibility: let \( K, J \subset I \), then the VMHS \( V_{Y_J} \) (ii) on \( Y_J \) and its limit VMHS on \( Y_{J,K} \) coincides with the VMHS \( V_{Y_{J,K}} \) limit of the VMHS \( V_X \), that is to say

\[ W(N_{J,K}, W_{Y_{J,K}}^0) = W(N_J, W_{Y_J}^0) \]

The last property is to be understood at each point \( y \in Y_{J,K} \) where \( W(N_J, W_{Y_J}^0) \) extends, moreover the above properties are not independent. In a study [25], Kashiwara deduce the properties (ii) to (iv) from the existence of \( M_i \) for \( i \in I \).

The VMHS is said to be graded polarised if for all \( r, Gr^W_0 \mathcal{L} \) is polarised.

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4.2 Local definition of the weight filtration.

For each subset $s_\lambda \subset I$ such that $Y_{s_\lambda} \neq \emptyset$ we write $W^{s_\lambda} = W(\Sigma_{i \in s_\lambda} N_i, W^0)$ for the filtration by subbundles defined by the nilpotent endomorphisms of the restriction $\mathcal{L}_{Y_{s_\lambda}}$ of $\mathcal{L}_X$ to $Y_{s_\lambda}$ (which exists by hypothesis), inducing also by restriction and for each subset $K \supset s_\lambda$ a filtration on $\mathcal{L}_{Y^*_K}$. We define the weight filtration $W'_s(s)$, locally near each point $y \in Y^*_M$, as in the case of $VHS$, in terms of a set of $n$ coordinates $y_i$, $i \in [1, n]$ where we identify $M$ with $[1, p]$ on an open set $U_y \simeq D^{[M]} \times D^{n-p}$ containing $y$ and a section $f^x = \Sigma_{J \subset M, J' \cap M = \emptyset} f_{J,J'}^x \frac{dy_J}{y_J} \wedge dy_{J'}$ of $\Omega^* \otimes \mathcal{L}_X$.

$$f^s_\lambda \in W^s_\lambda(\Omega^* \otimes \mathcal{L}_X)_{/U_y} \iff \forall J, N \subset M, f^s_{J,J'}/Y_N \cap U_y \in s_\lambda \in s_\lambda \subset N W^{s_\lambda}_{a_\lambda(J,I)} \mathcal{L}(Y_N \cap U_y)$$

It is a filtration by subcomplexes of analytic subsheaves globally defined on $X$. We deduce two filtrations $W'$ and $W$ of $\Omega^* \mathcal{L}$ as follows:

$$W' = s(W'(s))_{s, \in S(I)}, \quad W_r(s) = W'_s(s) \cap W^0_r, \quad W = s(W(s))_{s, \in S(I)}$$

Moreover the filtration $W^0$ extends as a constant filtration for all $s \in S(I)$ and the previous definition of the Hodge filtration $F$ remains unchanged. The filtrations $W'$ and $W$ will have different applications, the first leads to the filtration $W(N)$ on the nearby-cocycles and the second defines a $\text{MHS}$ on $X - Y$ when $X$ is proper.

Let $b \in Z$ and $K \subset M$; when the point $y$ is in $Y^*_K \subset Y^*_M$, the previous study apply to the nilpotent orbit $Gr_b^W$ defined at the point $y$ so that we can conclude that for $a > b$ (resp. $a < b$) the complex $C^a_K(Gr_b^W)$ is concentrated in degree $|K|$ (resp. $|K| - 1$) and acyclic for $a = b$. When the point $y$ vary in $Y^*_K$, the cohomology $H^{[K]}(C^a_K(Gr_b^W))$ is of weight $a - |K|$ induced by $W_{a-|K|}(N, W^0)$ and $F$ (resp. $H^{[K]-1}(C^a_K(Gr_b^W))$) of weight $a + |K|$, defines a local system $L_{a,K}^r$ on $Y^*_K$ which underlies a $VHS$ induced by $F$. We define as well the local system $L_{a,K}^r$ of general fiber $C^a_K(W^0_{a-1})$ equal to $H^{[K]}(C^a_K(W^0_{a-1}))$ is of weight $a - |K|$ induced by $W_{a-|K|}(N, W^0)$ and $F$, underlies a polarised $VHS$ induced by $F$ graded by $W^0$.

Theorem. Let $(\mathcal{L}, W', F)$ be a unipotent graded polarised good variation of mixed Hodge structures on $X - Y$; then the complex

$$(\Omega^* \mathcal{L}, W', W, W^0, F)$$

with the filtrations $W'$, $W$, $W^0$ and $F$ defined above satisfy the following decomposition and purity properties

i) Purity: For all subset $K \subset I$ and all integers $a > b$ (resp. $a < b$), the $VHS$ : $(L^K_a, W, F)$ of general fiber $H^{[K]}(C^a_K(Gr_b^W))$ (resp. $H^{[K]-1}(C^a_K(Gr_b^W))$) on $Y^*_K$, as well the $VHS$ : $(L^K_a, W, F)$ of general fiber $C^a_K(W^0_{a-1})$, graded polarised by $W^0$.

ii) The complex $Gr_a^W Gr_b^W(\Omega^* \mathcal{L})$ is acyclic, hence $Gr_a^W \Omega^* \mathcal{L} \simeq Gr_a^W W^0_{a-1} \Omega^* \mathcal{L} \oplus Gr_a^W W^0_{a-1} \Omega^* \mathcal{L}$

iii) Decomposition: We have the following decomposition into intermediate extensions on $Y_K$ of $\text{VHS} L^K_{a,b}$ (resp. $L^K_a$)

$$(Gr_a^W Gr_b^W \mathcal{L}, F) \simeq \oplus_{K \neq j, K \subset I} \mathcal{L}^K_{a,b}(-|K|, W[2 - |K|], F[-|K|]) \text{ if } a > b, \quad (f^K : Y_K \rightarrow Y_K),$$

$$(Gr_a^W Gr_b^W \Omega^* \mathcal{L}, F) \simeq \oplus_{K \neq j, K \subset I} \mathcal{L}^K_{a,b}(1 - |K|, W[-1], F) \text{ if } a < b, \quad Gr_a^W \Omega^* \mathcal{L} \simeq \oplus_{K \subset I} \mathcal{L}^K_{a,b}(-|K|, W[2 - |K|], F[-|K|]).$$

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iv) When $X$ is proper, the filtrations $W$ and $F$ define a $MHS$ on the cohomology of $X - Y$ with value in $\mathbb{L}$ and the filtration $W^0$ induces a filtration by $\text{sub} - MHS$.

Proof. i) Locally we reduce the problem to the study for $K \neq \emptyset$, $K \subset M \subset I$ of $C^K_a(Gr^W_b L)$ (resp. $C^K_M(Gr^W_b L)$) previously seen for the polarised nilpotent orbit $Gr^W_b L$, while the fiber of $j_a^K L_a$ at $y$ is the complex $C^K_a(M^0_{a-1} L)$. The complex $C^K_a(M^0_{a-1} L)$ for a nilpotent orbit $L$ defined at $y$ in $Y^K$ is a $VHS$ by successive extensions of $Gr^W_b L$ for $i < a$.

ii) The acyclicity reduces to the case of the $VHS$ : $Gr^W_a Y^* Gr^W_b L \simeq 0$, while the direct sum is similar to the case studied in (§2.II). Notice that: $Gr^W_a W^0_{a-1} L = Gr^W_a Y^* W^0_{a-1} L$.

iii) The assertions for $Gr^W_b L$ follow from the case of $VHS$, while the assertion for $W$ follows from (ii) whose right term appears in the case of $K \neq \emptyset$ and can be checked as successive extensions of $Gr^W_b L$ for $i < a$ using the count of weight as in the case of $VHS$ and following remark.

Remark: We use in the proof the fact that a bifiltered complex $(K, W^0, F)$ with $(K, W^0)$ defined over $\mathbb{R}$ and a finite increasing filtration $W^0$ such that $(Gr^W_r K, F)$ is a Hodge complex of weight $a$ for all $r$, then $(K, F)$ is a Hodge complex of weight $a$ and $W^0$ induces on cohomology a filtration by $\text{sub} - HS$.

iv) When $X$ is proper, the decomposition and purity results prove that the complex $(\Omega^* \mathbb{L}, W^r, W^0, F)$ is a filtered mixed Hodge complex according to the terminology of [13].

4.3 Nearby-cocycles $\Psi^r_j \mathbb{L}$

The constructions for $\Psi^r_j \mathbb{L}$ are similar to the case of $VHS$. We define the filtrations

$$W'_r(\Psi^r_j \mathbb{L})_{S(M)} = i^*_r s(W^r_r + 2p - 1 \Omega^* L[p], \eta)_{p \leq 0},$$

$$W^0_r(\Psi^r_j \mathbb{L})_{S(M)} = i^*_r s(\Omega^* W^0_r L[p], \eta)_{p \leq 0},$$

$$F^r_r(\Psi^r_j \mathbb{L})_{S(M)} = i^*_r s(F^r_r \Omega^* L[p], \eta)_{p \leq 0},$$

the action of the logarithm of the monodromy $\nu$ is defined similarly, then the relation for $a \geq 1$ and $b \in \mathbb{Z}$

$$\nu^a : Gr^W_{b+a} Gr^W_b \Psi^r_j \mathbb{L} \simeq Gr^W_{b-a} Gr^W_b \Psi^r_j \mathbb{L}$$

follows from the corresponding relation for $Gr^W_b L$ as a $VHS$ and this concludes that: $W^r$ is the relative monodromy filtration with respect to $W^0$ on $\Psi^r_j \mathbb{L}$. This isomorphism is equivalent to

Corollary: i) For all $a \geq 1$, $Gr^W_{b+a} Gr^W_b \text{kern} \nu^a = s(Gr^W_{b+a+2p-1} Gr^W_b \Omega^* L[p], \eta)_{-a \leq p \leq 0} \simeq 0$

ii) For $a > 0$, we have $Gr^W_{r+a} Gr^W_b \Psi^a \mathbb{L} \simeq s(Gr^W_{r+a+2p-1} Gr^W_b \Omega^* L[p], \eta)_{p \leq -a} \simeq 0$

$\oplus_{a+2p-1 \leq -a} Gr^W_{b+a+2p-1} Gr^W_b \Omega^* L[p]$ where only a finite number of $p$ give non zero terms.

iii) For $t > v \in \mathbb{Z}$, $Gr^W_r (W^0_t/W^0_v) \Psi^r_j \mathbb{L}$ decomposes into a direct sum of intermediate extensions of $VHS$ of weight $r$ graded polarised with respect to an induced filtration by $W^0$.

iv) For a proper morphism $f$, the complex $(\Psi^r_j \mathbb{L}, W^r, W^0, F)$ is a filtered mixed Hodge complex in the sense that for all $b < a$, $(W^0_b/W^0_a) \Psi^r_j \mathbb{L}, W^r, F)$ is a mixed Hodge complex.

The proof is similar to the case of $VHS$ and uses the remark above for successive extensions of $Gr^W_b L$. Notice the adjustment of the weight to $r$ in (iii) since we take the sum for $r = a + b$ with $a + 2p - 1 \leq 0$ that is the case of shift by 1 of the weight $s + 1$ of $(Gr^W_b \Omega^* Gr^W_a L)$ for $s \leq u$ which is compensated by $-1$ in the formula $r + 2p - 1$, while $2p$ is compensated by $p$ in the formula for $F$.
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References


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