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Some Abelian, Tauberian and Core Theorems Related to the (V,λ)-Summability

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Abstract

For a non-decreasing sequence of the positive integers tending to infinity $\lambda = (\lambda_m)$ such that $\lambda_{m+1} - \lambda_m \leq 1$, $\lambda_1 = 1$; (V,λ)-summability defined as the limit of the generalized de la Valée-Pousin of a sequence, [10]. In the present research, we establish some *Tauberian*, *Abelian* and *Core* theorems related to the (V,λ)-summability.

1. Preliminaries

Let $\mathbb{R}$ be the set of the reel numbers and $\mathbb{C}$ be the set of the complex numbers. Let c and ℓ_∞ be the space of all complex valued convergent and bounded sequences, one by one. Let $\lambda = (\lambda_m)$ be a non-decreasing sequence of the positive integers tending to ∞ such that $\lambda_1 = 1,\ \lambda_{m+1} \leq \lambda_m + 1$. A real number sequence $x = (x_n)$ is said to be (V,λ)-summable to the value l if

$$\lim_m t_m(x) = l$$

exists, where

$$t_m(x) = \frac{1}{\lambda_m} \sum_{n \in I_m} x_n, \quad I_m = [m - \lambda_m + 1, m].$$

By (V,λ), we mean the set of all (V,λ)-summable sequences, i.e.,

$$(V,\lambda) = \left\{ x = (x_n) : \lim_m t_m(x) = l \ \text{ for } \ \text{ some } \ l \in \mathbb{R} \right\}.$$

Also, by $(V,\lambda)_0$ we denote the space of all sequences which (V,λ)-summable to zero. It is clear that in the case $\lambda_m = m$ for all m, (V,λ)-summability reduces to the Cesáro summability, [11]. If $x \in (V,\lambda)$ and $\lim_m t_m(x) = l$, then we have $(V,\lambda) - \lim x = l$.
Let E be a subset of $\mathbb{N}$ (the set of natural numbers). Natural density δ of E given by the following equality:

$$\delta(E) = \lim_n \frac{1}{n} |\{k \leq n : k \in E\}|.$$

The number sequence $x = (x_k)$ is said to be statistically convergent to the number l if for every $\varepsilon > 0$, $\delta(\{k : |x_k - l| \geq \varepsilon\}) = 0$, [7]. In this case, we write: $st - \lim x = l$, where st and st_0 are the sets of all statistically convergent and statistically null sequences, respectively.
For a given non-negative regular matrix A, the number

$$\delta_A(K) = \lim_n \sum_{k \in K} a_{nk}$$

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is said to be the A-density of $K \subseteq \mathbb{N}$, [8]. A sequence $x=(x_k)$ is said to be A-statistically convergent to the number s if for every $\varepsilon>0$, the set $\{k:|x_k-s|\geq\varepsilon\}$ has A-density zero, [2]. Thus, the following equation is valid: $st_A-\lim x=s$. By $st(A)$ and $st(A)_0$, we respectively show the set of all A-statistically convergent and A-statistically null sequences.
For example, if we choose $E\subset\mathbb{N}$ such as $E=\{n^2:n=1,2,3\cdots\}$ then it is easy to see that $\delta(E)=0$. A real number sequence $x=(x_k)$ is said to be statistically convergence to the number l if for every $\varepsilon>0$, $\delta\{k:|x_k-l|\}=0$, [7]. For example, let

$$x_k=\begin{cases} k & , \quad k=n^2 \text{ for all } n=1,2,3,\cdots \\ \frac{1}{k} & , \quad \text{otherwise.}\end{cases}$$

Then it obvious that $\lim x_k$ does not exist. But since $\delta(E)=\delta(\{n^2:n=1,2,3\cdots\})=0$, we write $st-\lim x_k=\lim_k\frac{1}{k}=0$. If (x_k) is statistically convergence to a number l, then we write $st-\lim x=l$. By st and st_0, we denote the set of all statistically convergent and statistically null sequence, respectively. If a sequence is A-statistically convergent to l, then we can write $st_A-\lim x=l$.
Let $x=(x_k)$ be a sequence in $\mathbb{C}$ and R_k be the least convex closed region of complex plane containing $x_k,x_{k+1},x_{k+2},\ldots$. The Knopp Core (or $\mathscr{K}$-core) of x is defined by the intersection of all R_k (k=1,2,...), [1, pp.137]. In [12], it is indicate that

$$\mathscr{K}-core(x)=\bigcap_{z\in\mathbb{C}}B_x(z)$$

for any bounded sequence x, where $B_x(z)=\left\{w\in\mathbb{C}:|w-z|\leq\limsup_k|x_k-z|\right\}$.
In [6], the notion of the statistical core of a complex number sequence introduced by Fridy and Orhan [9] has been extended to the A-statistical core (or st_A-core) and it is shown that for a A-statistically bounded seqeunce x

$$st_A-core(x)=\bigcap_{z\in\mathbb{C}}C_x(z)$$

where $C_x(z)=\left\{w\in\mathbb{C}:|w-z|\leq st_A-\limsup|x_k-z|\right\}$. The inclusion theorems related to the $\mathscr{K}$-core and st_A-core has been worked by many authors [3–5].
Let D be an infinite matrix of complex entries d_{nk} and $x=(x_k)$ be a complex valued sequence. Then $Dx=\{(Dx)_n\}$ is called the transformed sequence of x, if $(Dx)_n=\sum_k d_{nk}x_k$ converges for each n. For two sequence spaces M and N we say that $D\in(M,N)$ if $Dx\in N$ for each $x\in M$. If M and N are equipped with the limits $M-\lim$ and $N-\lim$, respectively, $D\in(M,N)$ and $N-\lim_n(Dx)_n=M-\lim_k x_k$ for all $x\in M$, then we say D regularly transforms M into N and write $D\in(M,N)_{reg}$.
Recently, similar works studied by some authors, see [13–17]. In the present paper, we have proved some *Abelian*, *Tauberian* and *Core* theorems related to the (V,λ)-summability.

2. Tauberian and Abelian Theorems

For any sequence spaces X and Y, an *Abelian* theorem is a theorem such that states the inclusion $X\subset Y$. The *Tauberian* theorem is a one of the form $X\cap Z\subset Y$, where Z is also a sequence space and $Y\subset X$.
Our first result for (V,λ) is an *Abelian* theorem.

Theorem 2.1. *$c_{(C,1)}\subset(V,\lambda)$ if and only if*

$$\liminf_m\frac{m}{\lambda_m}=1, \tag{2.1}$$

where $c_{(C,1)}$ is the space of all Cesáro summable sequences.

Proof. Let $x\in c_{(C,1)}$ and

$$\lim_m\frac{1}{m}\sum_{n=1}^m x_n=l.$$

Then, for any given $\varepsilon>0$ and enough large m,

$$\left|\frac{1}{m}\sum_{n=1}^m x_n-l\right|<\varepsilon.$$

Now, one can write that

$$\begin{aligned}\left|\frac{1}{\lambda_m}\sum_{n\in I_m}(x_n-l)\right| &= \left|\frac{1}{\lambda_m}\sum_{n=1}^m(x_n-l)-\frac{1}{\lambda_m}\sum_{n=1}^{m-\lambda_m}(x_n-l)\right| \\ &\leq \frac{m}{\lambda_m}\left|\frac{1}{m}\sum_{n=1}^m(x_n-l)\right|+\frac{m-\lambda_m}{\lambda_m}\left|\frac{1}{m-\lambda_m}\sum_{n=1}^{m-\lambda_m}(x_n-l)\right| \\ &\leq \frac{m}{\lambda_m}\varepsilon+\frac{m-\lambda_m}{\lambda_m}\varepsilon \\ &\leq \varepsilon\left(2\frac{m}{\lambda_m}-1\right).\end{aligned}$$

Therefore, it is clear that $\lim_m t_m(x)=l$ if and only if (2.1) holds. This completes the theorem. ☐

Since $c \subset c_{(C,1)}$, the following result is obvious.

Corollary 2.2. *If (2.1) holds then* $c \subset (V,\lambda)$.

Theorem 2.3. $(V,\lambda)_0 \cap c_0 \subset (c_0)_{(C,1)}$*, where* $(c_0)_{(C,1)}$ *is the space of all Cesáro summable to zero sequences.*

Proof. Let $x \in (V,\lambda)_0 \cap c_0$. Thus, for any $\varepsilon > 0$ and enough large m,n, $|t_m(x)| \leq \varepsilon/2$ and $|x_n| \leq \varepsilon/2$. Hence, we have

$$\begin{aligned}\left|\frac{1}{m}\sum_{n=1}^{m} x_n\right| &= \left|\frac{1}{m}\sum_{n=1}^{m-\lambda_m} x_n + t_m(x)\right| \\ &\leq \frac{1}{m}\sum_{n=1}^{m-\lambda_m} |x_n| + \frac{\varepsilon}{2} \\ &\leq \frac{\varepsilon}{2}\left(1-\frac{\lambda_m}{m}+\frac{2}{m}\right).\end{aligned}$$

Also, since λ_m/m is bounded by 1, the following inequality is true:

$$\left|\frac{1}{m}\sum_{n=1}^{m} x_n\right| \leq \frac{\varepsilon}{m}$$

which gives the result. □

Since $(t_m(x)-l) \in (V,\lambda)_0$ and $(x_n - l) \in c_0$, we have the following outcome which is a *Tauberian* theorem.

Theorem 2.4. $(V,\lambda) \cap c \subset c_{(C,1)}$.

3. Core Theorems

Definition 3.1. *Let* R_m *be the least closed convex hull containing* $t_m, t_{m+1}, t_{m+2}, \ldots$*. Then,* $\mathcal{K}_\lambda$*-core of* x *is the intersection of all* R_m*, i.e.,*

$$\mathcal{K}_\lambda - core(x) = \bigcap_{m=1}^{\infty} R_m.$$

In fact, we define $\mathcal{K}_\lambda$-core of x by the $\mathcal{K}$-core of the sequence (t_m). Thus, one may state the following theorem which is an parallel of $\mathcal{K}$-core.
One can prove the following theorem by replacing (t_m) in place of (x_k), which is analogues of theorem given in [12] for Knopp core.

Theorem 3.2. *Let, for any* $z \in \mathbb{C}$*,*

$$G_x(z) = \left\{ w \in \mathbb{C} : |w-z| \leq \limsup_m |t_m(x) - z| \right\}.$$

So, for any $x \in \ell_\infty$*,*

$$\mathcal{K}_\lambda - core(x) = \bigcap_{z\in\mathbb{C}} G_x(z).$$

At present, we are in a position to construct the inclusion theorems. First of all, we prove several lemmas which will be helpful to the proof of the next theorems.

Lemma 3.3. *Let* X *be any sequence space. Then,* $B \in (X,(V,\lambda))$ *if and only if* $D \in (X,c)$*, where* $D = (d_{nk})$ *is defined by*

$$d_{nk} = \left\{ \frac{1}{\lambda_n}\sum_{j\in I_n} b_{jk},\ (n \in \mathbb{N}) \right\}. \tag{3.1}$$

Proof. Let $x \in X$ and take into consideration the equality

$$\frac{1}{\lambda_m}\sum_{j\in I_m}\sum_{k=0}^{n} b_{jk}x_k = \sum_{k=0}^{n}\frac{1}{\lambda_m}\sum_{j\in I_m} b_{jk}x_k;\ (m,n \in \mathbb{N})$$

which yields as $n \longrightarrow \infty$ that

$$\frac{1}{\lambda_m}\sum_{j\in I_m}(Bx)_j = (Dx)_m;\ (m \in \mathbb{N}),$$

where $D = (d_{nk})$ is defined by (3.1).
Thus, it is obvious that $B \in (X,(V,\lambda))$ if and only if $D \in (X,c)$. As a result, the proof is complete. □

For the special cases of the sequence space X, one can state the following lemmas.

Lemma 3.4. *$B\in(c,\ (V,\lambda))_{reg}$ if and only if*

$$\sup_m \sum_k \left| \frac{1}{\lambda_m} \sum_{n\in I_m} b_{nk} \right| < \infty,$$

$$\lim_m \frac{1}{\lambda_m} \sum_{n\in I_m} b_{nk} = 0, \forall k,$$

$$\lim_m \sum_k \frac{1}{\lambda_m} \sum_{n\in I_m} b_{nk} = 1.$$

Following lemma is an analogues of Theorem 3.2 in [4]. One can prove it by same technique. So, we omit the proof.

Lemma 3.5. *$B\in(st(A)\cap\ell_\infty,(V,\lambda))_{reg}$ if and only if $B\in(c,(V,\lambda))_{reg}$ and*

$$\lim_m \sum_{k\in E} \frac{1}{\lambda_m} \Big| \sum_{n\in I_m} b_{nk} \Big| = 0 \tag{3.2}$$

for every $E\subset\mathbb{N}$ with $\delta_A(E)=0$.

By choosing A as Cesáro matrix

$$a_{nk} = \begin{cases} 1/n & , \quad n\geq k \\ 0 & , \quad \text{others.} \end{cases}$$

we get following lemma.

Lemma 3.6. *$B\in(S\cap\ell_\infty,(V,\lambda))_{reg}$ if and only if $B\in(c,(V,\lambda))_{reg}$ and*

$$\lim_m \sum_{k\in E} \frac{1}{\lambda_m} \Big| \sum_{n\in I_m} b_{nk} \Big| = 0$$

for every $E\subset\mathbb{N}$ with $\delta(E)=0$.

Now, we can give the following theorem.

Theorem 3.7. *Let $\|B\|=\sup_n\sum_k|b_{nk}|<\infty$. Then, $\mathscr{K}_\lambda$-core$(Bx)\subseteq\mathscr{K}$-core(x) for all $x\in\ell_\infty$ if and only if $B\in(c,(V,\lambda))_{reg}$ and*

$$\lim_m \sum_k \frac{1}{\lambda_m} \Big| \sum_{n\in I_m} b_{nk} \Big| = 1. \tag{3.3}$$

Proof. (*Necessity*). Let $x\in c$ with $\lim x=l$. Then, $\mathscr{K}$-core$(x)=\{l\}$ which implies that $\mathscr{K}_\lambda$-core$(Bx)\subseteq\{l\}$. Since the assumption $\|B\|<\infty$ implies the boundedness of Bx, $\mathscr{K}_\lambda$-core$(Bx)=\{l\}$ and therefore $(V,\lambda)-\lim Bx=l$. This implies that $B\in(c,(V,\lambda))_{reg}$.
Let's assume that the condition(3.3) is not satisfy. Then we have,

$$\lim_m \sum_k \frac{1}{\lambda_m} \Big| \sum_{n\in I_m} b_{nk} \Big| > 1.$$

The conditions of the Lemma 3.4 give us to choose two strictly increasing sequences $\{k(n_i)\}$ and $\{n_i\}$ $(i=1,2,\ldots)$ of positive integers such that

$$\sum_{k=0}^{k(n_i-1)} \frac{1}{\lambda_m} \Big| \sum_{n\in I_m} b_{n_i,k} \Big| < \frac{1}{4}, \quad \sum_{k=k(n_{i-1})+1}^{k(n_i)} \frac{1}{\lambda_m} \Big| \sum_{n\in I_m} b_{n_i,k} \Big| > 1+\frac{1}{2}$$

and

$$\sum_{k=k(n_i)+1}^{\infty} \frac{1}{\lambda_m} \Big| \sum_{n\in I_m} b_{n_i,k} \Big| < \frac{1}{4}.$$

At present, let's define a sequence $x=(x_k)$ by

$$x_k = sgn\Big(\frac{1}{\lambda_m} \sum_{n\in I_m} b_{n_i,k} \Big), \quad k(n_{i-1})+1\leq k<k(n_i),$$

where m is an integer as defined in the choosing $\lambda=\lambda_m$. Then, it is clear that $\mathscr{K}$-core$(x)\subseteq B_x(0)$. Also,

$$\Big| \sum_k \frac{1}{\lambda_m} \sum_{n\in I_m} b_{n_i,k} x_k \Big| \geq \sum_{k=k(n_{i-1})+1}^{k(n_i)} \frac{1}{\lambda_m} \Big| \sum_{n\in I_m} b_{n_i,k} \Big| - \sum_{k=0}^{k(n_i-1)} \frac{1}{\lambda_m} \Big| \sum_{n\in I_m} b_{n_i,k} \Big| - \sum_{k=k(n_i)+1}^{\infty} \frac{1}{\lambda_m} \Big| \sum_{n\in I_m} b_{n_i,k} \Big| > 1+\frac{1}{2}-\frac{1}{4}-\frac{1}{4}=1.$$

Since $B\in(c,(V,\lambda))_{reg}$, it follows that (Bx) has a subsequence whose (V,λ)-limit can not be in $B_x(0)$. This is a contradiction with that $\mathscr{K}_\lambda$-core$(Bx)\subseteq\mathscr{K}$-core(x). Hence, the condition (3.3) have to be satisfy.

(*Sufficiency*). Let $w \in \mathscr{K}_\lambda$-core$(Bx)$. So, for any given $z \in \mathbb{C}$, one get

$$\begin{aligned} |w-z| &\leq \limsup_m |t_m(Bx)-z| \\ &= \limsup_m \Big|z - \sum_k c_{mk} x_k\Big| \\ &\leq \limsup_m \Big|\sum_k c_{mk}(z-x_k)\Big| + \limsup_m |z| \Big|1 - \sum_k c_{mk}\Big| \\ &= \limsup_m \Big|\sum_k c_{mk}(z-x_k)\Big| \end{aligned} \tag{3.4}$$

where

$$c_{mk} = \frac{1}{\lambda_m} \sum_{n \in I_m} b_{nk}.$$

Now, let $\limsup_k |x_k - z| = l$. Subsequently, for any $\varepsilon > 0$, $|x_k - z| \leq l + \varepsilon$ whenever $k \geq k_0$. Thus, the following inequality applies:

$$\begin{aligned} \Big|\sum_k c_{mk}(z-x_k)\Big| &= \Big|\sum_{k<k_0} c_{mk}(z-x_k) + \sum_{k \geq k_0} c_{mk}(z-x_k)\Big| \\ &\leq \sup_k |z-x_k| \sum_{k<k_0} |c_{mk}| + (l+\varepsilon) \sum_{k \geq k_0} |c_{mk}| \\ &\leq \sup_k |z-x_k| \sum_{k<k_0} |c_{mk}| + (l+\varepsilon) \sum_k |c_{mk}|. \end{aligned} \tag{3.5}$$

Therefore, applying $\limsup_m$ and combining (3.4) with (3.5), we have

$$|w-z| \leq \limsup_m \Big|\sum_k c_{mk}(z-x_k)\Big| \leq l$$

which shows that $w \in \mathscr{K}$-core(x). The proof is completed. □

Theorem 3.8. *Let $\|B\| = \sup_n \sum_k |b_{nk}| < \infty$. Then, $\mathscr{K}_\lambda$-core$(Bx) \subseteq st_A$-core(x) for all $x \in \ell_\infty$ if and only if $B \in (st(A) \cap \ell_\infty, (V,\lambda))_{reg}$ and the condition (3.3) are satisfy.*

Proof. (*Necessity*). By choosing $x \in st(A) \cap \ell_\infty$, as in Theorem 3.7, we immediately have that $B \in (st(A) \cap \ell_\infty, (V,\lambda))_{reg}$.
On the other hand, since st_A-core$(x) \subseteq \mathscr{K}$-core$(x)$ for any sequence x [6], the necessity of the condition (3.3) follows from Theorem 3.7.
(*Sufficiency*). Let we take $w \in \mathscr{K}_\lambda$-core$(Bx)$. So, we have again the condition (3.4). At present, if $st_A - \limsup |x_k - z| = s$, then for any $\varepsilon > 0$, the set E defined by $E = \{k : |x_k - z| > s + \varepsilon\}$ has zero A-density. At present, we get

$$\begin{aligned} \Big|\sum_k c_{mk}(z-x_k)\Big| &= \Big|\sum_{k \in E} c_{mk}(z-x_k) + \sum_{k \notin E} c_{mk}(z-x_k)\Big| \\ &\leq \sup_k |z-x_k| \sum_{k \in E} |c_{mk}| + (s+\varepsilon) \sum_{k \notin E} |c_{mk}| \\ &\leq \sup_k |z-x_k| \sum_{k \in E} |c_{mk}| + (s+\varepsilon) \sum_k |c_{mk}|. \end{aligned}$$

Hence, applying the operator $\limsup_m$ and using the condition (3.3) with (3.2), we can write that

$$\limsup_m \Big|\sum_k c_{mk}(z-x_k)\Big| \leq s + \varepsilon. \tag{3.6}$$

Finally, combining (3.4) with (3.6), we get

$$|w-z| \leq st_A - \limsup_k |x_k - z|$$

which shows that $w \in st_A$-core(x). □

As a consequence of Theorem 3.8, we get

Corollary 3.9. *Let $\|B\| = \sup_n \sum_k |b_{nk}| < \infty$. Then, $\mathscr{K}_\lambda$-core$(Bx) \subseteq st$-core(x) for all $x \in \ell_\infty$ if and only if $B \in (st \cap \ell_\infty, (V,\lambda))_{reg}$ and (3.3) holds.*

4. Conclusion

In this paper, we obtained new some *Tauberian*, *Abelian* and *Core* theorems related to the (V,λ)-summability.

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Author's contributions

All authors contributed equally to the writing of this paper. All authors read and approved the final manuscript.

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