Ω, to X. If every $\mu \in \mathcal{M}$ has the regular p-variation (in the sense of [3]) and the set $\{p(\mu(D))x\ ;\ \mu \in \mathcal{M}\}$ is bounded for every open set D, then

$$\{p(\mu(B))\ ;\ \mu \in \mathcal{M},\ B \in \mathcal{B}\}$$

is a bounded set for every $p \in \mathcal{P}$.

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WEAK PSEUDOUNIFORM STRUCTURES

BY

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1. Introduction. In [6] we define the weak pseudouniform structure on $L^1(X, \mathcal{A}, \mu)$ and we obtain an extension of the classical result of weak compactness due to Dunford and Pettis.

The purpose of this paper is the sequential variant of this extension. In 2. we introduce the weak pseudouniform structure on a normed linear space and we generalize the part "weak compactness → weak sequentially compactness" of Eberlein-Šmulian's theorem. In section 3. we use this generalization to $L^1(X, \mathcal{A}, \mu)$.

2. Weak pseudouniform structure. Let $(X, \|.\|)$ be a normed linear space and X^* be the topological dual of X. For every $a \geqslant 0$, $x^* \in X^*$ and $\varepsilon > 0$, let us denote:

$$U^a_{x^*,\varepsilon} = \{(x, y) \in X \times X : |x^*(x-y)| < a\|x^*\| + \varepsilon\}.$$

For every $a \geqslant 0$, $\mathcal{S}_a = \{U^a_{x^*,\varepsilon} : x^* \in X^*,\ \varepsilon > 0\}$ is a subbase for a semiuniformity $\mathcal{U}_a$ on X (see [2]). Let $\mathcal{U} = \{\mathcal{U}_a : a \geqslant 0\}$; then, for every $a \geqslant 0$ and $U \in \mathcal{U}_a$, there exists $V \in \mathcal{U}_{a/2}$ such that $V \circ V \subseteq U$. Furthermore, $a \leqslant b$ implies $\mathcal{U}_a \supseteq \mathcal{U}_b$. It follows that $\mathcal{U}$ is a pseudouniformity on X with respect to the directed set $(R_+, \leqslant^{-1})$ (see [6]). We remark that $\mathcal{U}_0$ is the weak uniformity on X and, for every $a \geqslant 0$, $\mathcal{U}_a \subseteq \mathcal{U}_0$. We say that $\mathcal{U}$ is *the weak pseudouniformity* on X.

For every set $A \subseteq X$, we denote by $\bar{A}$ the closure of A in the norm topology and by $\bar{A}^a$ the closure of A in the semiuniform space $(X, \mathcal{U}_a)$.

Proposition 1. *Let A be a subspace of the normed linear space X. Then, for every $a \geqslant 0$, $\bar{A} \subseteq \bar{A}^a \subseteq T(\bar{A}, a)$, where* $T(\bar{A}, a)$ is the closed sphere which has *$\bar{A}$ for center and a for radius.*

Proof. Obviously, $\bar{A} \subseteq \bar{A}^a$. Now, if $x \in \bar{A}^a - \bar{A}$, then $d(x, \bar{A}) = d > 0$. Hence there is a point $x^* \in X^*$ with $x^*(x) = 1$, $x^*(y) = 0$, for every $y \in \bar{A}$ and $\|x^*\| = 1/d$([5, II.3.12]). For any $\varepsilon > 0$ there is a point $y \in A$ such that $|x^*(x-y)| < a\|x^*\| + \varepsilon$. Therefore, $1 < a.1/d + \varepsilon$, so that $d \leqslant a$. It follows that $x \in T(\bar{A}, a)$.

Remark. If $a = 0$ than $\bar{A} = \bar{A}^0$, where $\bar{A}^0$ is the weak closure of A. So, we rediscover a classical result.

A set $A \subseteq X$ is **a-relatively compact (a-relatively sequentially compact)** *if every net in A has a cluster point (every sequence in A has a convergent subsequence) in semiuniform space $(X, \mathcal{U}_a)$.*

We remark that the sequence (x_n) converges to x in semiuniform space $(X, \mathcal{U}_a)$ if and only if $\overline{\lim_n} |x^*(x_n - x)| \leqslant a.\|x^*\|$, for every $x^* \in X^*$.

Theorem 1. *Let $a \geq 0$ and $A \subseteq X$; if A is an a-relatively compact set then A is $5a$-relatively sequentially compact set.*

Proof. Let A be an a-relatively compact set in X, $(x_n)_{n\geq 1}$ be an arbitrary sequence in A and x_0 be a cluster point of $(x_n)_{n\geq 1}$ in $(X, \mathfrak{U}_a)$, i.e., for every $\varepsilon > 0$, $y_1^*, \ldots, y_p^* \in X^*$ and $n \in N$, there exists $k \geq n$ such that $|y_i^*(x_k - x_0)| < a.\|y_i^*\| + \varepsilon$, $i = 1, 2, \ldots, p$.

Let $X_0 = \overline{sp}\{x_0, x_1, \ldots, x_n, \ldots\}$. Then X_0 is a separable subspace of X, so that the closed unit sphere S_0^* in X_0^* is $\sigma(X_0^*, X_0)$-separable (see [5, Theorems V. 5.1 and V. 4.2]). Let H_0 be a countable dense set in S_0^*; each element of H_0 can be extended to an $x^* \in X^*$ with $\|x^*\| \leq 1$. We denote by $H = \{x_1^*, x_2^*, \ldots x_n^*, \ldots\}$ the set of these extensions. By a diagonal process we may extract a subsequence (x_{k_n}) of (x_n) such that, for every $p \in N^*$ and $i = 1, 2, \ldots, p$, $|x_i^*(x_{k_n} - x_0)| < a.\|x_i^*\| + 1/n$. Now, for every $x^* \in H$, there exists $n_0 \in N$ such that $x^* \in \{x_1^*, \ldots, x_n^*\}$, for every $n \geq n_0$. Hence we have $|x^*(x_{k_n} - x_0)| < a \cdot \|x^*\| + 1/n$, for every $n \geq n_0$, so that, $\overline{\lim_n} |x^*(x_{k_n} - x_0)| \leq a\|x^*\| \leq 5a \cdot \|x^*\|$. It remains to show that:

$$\overline{\lim_n} \, | x^*(x_{k_n} - x_0) | \leq 5a \cdot \|x^*\|, \quad \text{for every} \quad x^* \in X^*. \tag{1}$$

If this is not true, there exists an $x_0^* \in X^*$, an $\varepsilon_0 > 0$ and a subsequence (y_n) of (x_{k_n}) such that:

$$|x_0^*(y_n - x_0)| > 5a\|x_0^*\| + \varepsilon_0, \quad \text{for every } n \in N. \tag{2}$$

But A is a-relatively compact, hence we obtain a point $y_0 \in X$ such that every neighborhood of y_0 in $(X, \mathfrak{U}_a)$ contains at least one y_n. Therefore $y_0 \in \overline{X}_0^w$ and from Proposition 1, $y_0 \in T(\overline{X}_0, a) = T(X_0, a)$. Hence, there exists a point $z_0 \in X_0$ such that:

(3) $\|y_0 - z_0\| \leq a$. Let $y_0^* = x_0^* / \|x_0^*\|$. Just as above, we may extract a subsequence (y_{k_n}) of (y_n) such that:

$$\overline{\lim_n} |x^*(y_{k_n} - y_0)| \leq a \cdot \|x^*\|, \text{ for every } x^* \in H_1 = \{y_0^*, x_1^*, \ldots, x_n^*, \ldots\} \tag{4}$$

Now, for every $x^* \in H$ and $n \in N$ we have $|x^*(x_0 - y_0)| \leq |x^*(y_{k_n} - x_0)| + |x^*(y_{k_n} - y_0)|$, so that:

$$|x^*(x_0 - y_0)| \leq \overline{\lim_n} |x^*(y_{k_n} - x_0)| + \overline{\lim_n} |x^*(y_{k_n} - y_0)| \leq 2a\|x^*\| \leq 2a. \tag{5}$$

Because H_0 is $\sigma(X_0^*, X_0)$-dense in S_0^* and $y_0^*|X_0 \in S_0^*$, for every $\varepsilon > 0$, there exists $x^* \in H$ such that $|x^*(x_0 - z_0) - y_0^*(x_0 - z_0)| < \varepsilon$ $(x_0 - z_0 \in X_0)$. Then, from (5) and (3) we obtain: $|y_0^*(x_0 - z_0)| \leq |y_0^*(x_0 - z_0) - x^*(x_0 - z_0)| + |x^*(x_0 - z_0)| < \varepsilon + |x^*(x_0 - y_0)| + |x^*(y_0 - z_0)| \leq \varepsilon + 2a + \|x^*\| \cdot \|y_0 - z_0\| \leq 3a + \varepsilon$. Hence we have:

$$|y_0^*(x_0 - z_0)| \leq 3a. \tag{6}$$

Now, from (2) we have:

$$5a + \varepsilon_0 / \|x_0^*\| < |y_0^*(y_{k_n} - x_0)| \leq |y_0^*(y_{k_n} - y_0)| + |y_0^*(y_0 - x_0)|,$$

for every $n \in N$. Hence, from (4) and (6) we have: $5a + \varepsilon_0/\|x_0^*\| \leq a + |y_0^*(z_0 - x_0)| + |y_0^*(y_0 - z_0)| \leq 4a + \|y_0 - z_0\|$. But this fact contradicts (3). Hence (1) is true, so that (x_{k_n}) converges to x_0 in the semiuniform space $(X, \mathfrak{U}_{5a})$. It follows that A is a $5a$-relatively sequentially compact set.

We remark that a set A is 0-relatively compact (0-relatively sequentially compact) is and only if A is relatively weakly compact (relatively weakly sequentially compact). Hence, from Theorem 1, we obtain for $a = 0$:

Corollary 1. *Every relatively weakly compact set is relatively weakly sequentially compact.*

3. Weak pseudouniformity on $L^1(X, \mathcal{A}, \mu)$. Let X be a set, $\mathcal{A}$ be a σ-algebra of subsets of X and μ be a positive, finite, countably additive measure on X. We remark that, in this case, the topological dual of L^1 is L^∞. Therefore, for every $a \geq 0$, $h \in L^\infty$ and $\varepsilon > 0$ we have

$$U_{h,\varepsilon}^a = \{(f, g) \in L^1 \times L^1 : |\int_X (f - g) \cdot h d\mu| < a\|h\|_\infty + \varepsilon\}.$$

If $\mathcal{S}_a = \{U_{h,\varepsilon}^a : h \in L^\infty, \varepsilon > 0\}$ then the weak pseudouniformity on L^1 is $\mathfrak{U} = \{\mathfrak{U}_a : a \geq 0\}$, where, for every $a \geq 0$, $\mathcal{S}_a$ is a subbase for the semiuniformity $\mathfrak{U}_a$. We say that the sequence $(f_n) \subseteq L^1$ is a-convergent to f if (f_n) converges to f in the semiuniform space $(L^1, \mathfrak{U}_a)$. Therefore, (f_n) is a-convergent to f iff:

$$\overline{\lim_n} |\int_X (f_n - f) \cdot g d\mu| \leq a \cdot \|g\|_\infty, \quad \text{for every} \quad g \in L^\infty.$$

Proposition 2. *A set $H \subseteq L^1$ is a norm bounded set if and only if the set $\{\int_A f d\mu : f \in H\}$ is a bounded set, for every $A \in \mathcal{A}$.*

Proof. If $H \subseteq L^1$ is a norm bounded set then H is weakly bounded set; hence, for every $h \in L^\infty$, $\{\int_X f \cdot h d\mu : f \in H\}$ is a bounded set. Particularly, for every $A \in \mathcal{A}$, $\{\int_A f d\mu : f \in H\}$ is a bounded set. Now, suppose that, for every $A \in \mathcal{A}$, $\{\int_A f d\mu : f \in H)$ is a bounded set. Let $\nu_f : \mathcal{A} \to R$, $\nu_f(A) = \int_A f d\mu$. Then, for each $A \in \mathcal{A}$, $\sup\{|\nu_f(A)| : f \in H\} < +\infty$. From Nikodym-Grothendieck boundedness theorem (see [4, pp. 80]), $\sup\{|\nu_f(A)| : f \in H, A \in \mathcal{A}\} = M < +\infty$. For every $f \in H$, let us denote by $P(f) = \{x \in X : f(x) \geq 0\}$ and $N(f) = \{x \in X : f(x) < 0\}$. Then $\|f\|_1 = \int_X |f| d\mu = \int_{P(f)} f d\mu - \int_{N(f)} f \, d\mu \leq |\nu_f(P(f))| + |\nu_f(N(f))| \leq 2M$, for every $f \in H$, so that H is a norm bounded set.

Corollary 2. *Every a-convergent sequence of L^1 is a norm bounded sequence.*

Proof. Let (f_n) be a sequence which converges to f in $(L^1, \mathfrak{U}_a)$. Then, for every $A \in \mathcal{A}$, $\overline{\lim_n} |\int_A (f_n - f) d\mu| \leq a$, so that $\{\int_A f_n d\mu : n \in N\}$ is a bounded set, for every $A \in \mathcal{A}$.

Let $\mathcal{S}(\mathcal{A})$ be the set of all simple functions, i.e. the set of the functions $f = \sum_{i=1}^n a_i \chi_{A_i}$, where $a_1, \ldots, a_n$ are scalars and $A_1, \ldots, A_n$ are disjoint members of $\mathcal{A}$ (χ_A is the characteristic function of A).

Proposition 3. *The sequence (f_n) is a-convergent to f if and only if* $\overline{\lim_n} |\int_X (f_n - f) g d\mu| \leq a \cdot \|g\|_\infty$, *for every* $g \in \mathcal{S}(\mathcal{A}) \cap L^\infty$.

Proof. The necessity of this condition is clear. For every $A\in\mathcal{A}$, $\chi_A\in\mathcal{S}(\mathcal{A})\cap L^\infty$, so that $\overline{\lim_n}\,|\int_A (f_n-f)d\mu|\leq a$. Then $\{\int_A (f_n-f)d\mu : n\in N\}$ is bounded, for every $A\in\mathcal{A}$. From Proposition 2 it follows that $\sup\{\|f_n-f\|_1 : n\in N\}=M<+\infty$. For every $g\in L^\infty$ and $\varepsilon>0$, there is $g_\varepsilon\in\mathcal{S}(\mathcal{A})\cap L^\infty$ such that $\|g-g_\varepsilon\|<\varepsilon/M+a$. Therefore, $\overline{\lim_n}\,|\int_X (f_n-f)g d\mu|\leq\overline{\lim_n}\int_X |f_n-f|\,|g-g_\varepsilon|\,d\mu+\overline{\lim_n}\,|\int_X (f_n-f)g_\varepsilon d\mu|\leq\overline{\lim_n}\,\|f_n-f\|_1\cdot\|g-g_\varepsilon\|_\infty+a\cdot\|g_\varepsilon\|_\infty\leq M\cdot\varepsilon/(M+a)+a(\varepsilon/M+a+\|g\|_\infty)=a\cdot\|g\|_\infty+\varepsilon$. It follows that (f_n) is a-convergent to f.

Proposition 4. a) *If (f_n) is a-convergent to f then we have:*

$$(*)\ \overline{\lim_n}\,|\int_A (f_n-f)\,d\mu|\leq a,\ \text{for every } A\in\mathcal{A}.$$

b) *If the condition $(*)$ is satisfied then (f_n) is $2a$-convergent to f.*

Proof. The part a). is a consequence of the definition of a-convergence.

b) For every $g\in\mathcal{S}(\mathcal{A})\cap L^\infty$, $g=\sum_{i=1}^n a_i\chi_{A_i}$, let $\mathcal{F}=\{\bigcup_{i\in I} A_i : I\subseteq\{1,2,\ldots,p\}\}$. Obviously, $\mathcal{F}$ is a finite subclass of $\mathcal{A}$. From $(*)$, for every $\varepsilon>0$ there is an $n_0\in N$ such that, for every $n\geq n_0$ and $A\in\mathcal{F}$ we have:

$$(1)\qquad |\int_A (f_n-f)d\mu|<a+\varepsilon/2\|g\|_\infty.$$

Now, $|\int_X (f_n-f)gd\mu|=|\sum_{i=1}^p a_i\int_{A_i}(f_n-f)d\mu|\leq\sum_{i=1}^p|\int_{A_i}(f_n-f)d\mu|\cdot\max\{|a_i| : i=1,2,\ldots,p\}=\sum_{i=1}^p|\int_{A_i}(f_n-f)d\mu|\cdot\|g\|_\infty$. There is a partition $\{I_1,I_2\}$ of $\{1,2,\ldots,p\}$ such that $\int_{A_i}(f_n-f)d\mu\geq 0$, for every $i\in I_1$ and $\int_{A_i}(f_n-f)d\mu<0$, for every $i\in I_2$. Therefore, $|\int_X (f_n-f)g\,d\mu|\leq(\sum_{i\in I_1}\int_{A_i}(f_n-f)d\mu-\sum_{i\in I_2}\int_{A_i}(f_n-f)d\mu)\cdot\|g\|_\infty=|\int_{B_1}(f_n-f)d\mu|\cdot\|g\|_\infty+|\int_{B_2}(f_n-f)d\mu|\cdot\|g\|_\infty$, where $B_1=\bigcup\{A_i : i\in I_1\}$, $B_2=\bigcup\{A_i : i\in I_2\}\in\mathcal{F}$. Hence, from (1), $|\int_{B_k}(f_n-f)d\mu|<a+\varepsilon/2\cdot\|g\|_\infty$, $k=1,2$, so that, $|\int_X (f_n-f)gd\mu|<(2a+\varepsilon/\|g\|_\infty)\cdot\|g\|_\infty=2a\cdot\|g\|_\infty+\varepsilon$. It follows that $\overline{\lim_n}\,|\int_X (f_n-f)gd\mu|\leq 2a.\|g\|_\infty$, for every $g\in\mathcal{S}(\mathcal{A})\cap L^\infty$. From Proposition 3, (f_n) is $2a$-convergent to f.

In the case $a=0$ we obtain the following classical result.

Corollary 3. *The sequence (f_n) in L^1 converges weakly to f in L^1 if and only if $\int_A fd\mu=\lim_n\int_A f_n d\mu$, for each $A\in\mathcal{A}$.*

The notion of uniform integrability index was introduced by J. Appell and E. De Pascale in [1, 3.4]. So, for every $H\subseteq L^1$ we denote by $c(H)=\inf_{\varepsilon>0}\sup\{\sup_{f\in H}\int_A|f|\,d\mu : A\in\mathcal{A},\ \mu(A)<\varepsilon\}$. We remark that $c(H)=0$ if and only if H is an uniformly integrable subset of L^1.

In [6, Theorem 1) we proved that every bounded set $H\subseteq L^1$ is $c(H)$relatively compact. Then, from Theorem 1, it follows:

Corollary 4. *Every bounded set $H\subseteq L^1$ is $5c(H)$ — relatively sequentialy compact set.*

Let $q(H)=\inf\{a>0 : H$ is a — relatively sequentially compact set in $L^1\}$. Then, from Corollary 4 and [6, Theorem 2] we obtain:

Corollary 5. *For every bounded set $H\subseteq L^1$ we have:*

$$1/8\cdot c(H)\leq q(H)\leq 5\cdot c(H).$$

From Corollary 5, we obtain:

Corollary 6. (Dunford — Pettis *Theorem*) *A bounded subset $H\subseteq L^1$ is relatively weakly sequentially compact if and only if H is uniformly integrable.*

Using Eberlein—Šmulian's theorem, we can give an improvement of the right hand inequality of Corollary. 5. For every nonvoid bounded subset H of a Banach space E, $F.\ S.$ De Blasi has introduced the weak measure of noncompactness of H: $\omega(H)=\inf\{t>0$: there exists C — weakly compact subset of E such that $H\subseteq C+tB\}$, where $B=\{x\in E : \|x\|\leq 1\}$ (see [3]). In the aforementioned paper[1]. J. Appell and E. De Pascale have proved that, for every bounded subset $H\subseteq L^1$, $c(H)=\omega(H)$.

Proposition 5. *For every bounded set $H\subseteq L^1$, we have $q(H)\leq c(H)$.*

Proof. For every $a>c(H)=\omega(H)$ there exist a number t with $0<t<a$ and an weakly compact set $C\subseteq L^1$ such that $H\subseteq C+t\cdot B$. For every sequence $(f_n)\subseteq H$ there exist $(g_n)\subseteq C$ and $(h_n)\subseteq B$ such that $f_n=g_n+t\cdot h_n$. From Eberlein-Šmulian's theorem, C is weakly sequentially compact, hence there exists a subsequence (g_{k_n}) of (g_n) which is weak convergent to a function $f\in L^1$.

Hence, for every $u\in L^\infty$, $\overline{\lim}|\int_X(f_n-f)ud\mu|\leq\overline{\lim}|\int(g_n-f)\,ud\mu|+\overline{\lim}|\int_X t.h_n\cdot ud\mu|\leq t\cdot\overline{\lim}\,\|h_n\|_1\cdot\|u\|_\infty\leq t\cdot\|u\|_\infty<a.\|u\|_\infty$, so that (f_n) is a-convergent to f. Therefore H is an a-relatively sequentially compact set. Hence, for every $a>c(H)$ we have $q(H)\leq a$, so that $q(H)\leq c(H)$.

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