

Applications of Theorem Arens-Michael

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Proceedings of the European Integration between Tradition
and Modernity

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Oktober, 22-23, 2009

Abstract

We characterize locally, m -convex, complete algebras as being projective limit of projective system of Banach algebras with the aid of Arens-Michael theorem.

1 Introduction

For a normed complex unitary algebra $(A, \|\cdot\|)$ we define the set: $D(A, \|\cdot\|; 1) = \{f \in A' | f(1) = 1 \text{ and } \|f\| = 1\}$. For any $a \in A$ we define numerical range of a the set

$$V(A, \|\cdot\|; a) = \{f(a) | f \in D(A, \|\cdot\|; 1)\},$$

and numerical radius the set:

$$v(A, \|\cdot\|; a) = \sup\{|\lambda| | \lambda \in V(A, \|\cdot\|; 1)\}.$$

The set $D(A, \|\cdot\|; 1)$ is a convex subset, weak compact of A' and numerical range $V(A, \|\cdot\|; a)$ is also a compact subset of \mathbf{C} , [2].

The properties and applications of numerical ranges on a normed algebra have been largely studied and the main results have been presented by F.F. Bonsall and J.Duncan [2]. The m -convex locally algebras have been thoroughly examined by E.A. Michael in [5].

We observe that for a given m -convex locally algebra A , with unital 1 there exists an increasingly family of submultiplicatively seminormes $\{p_\alpha\}$ on A which generates the topology such that $p_\alpha(1) = 1$ for all α . Given this algebra we denote with $P(A)$ the class of all these family of seminormes on A

and with $(A, \{p_\alpha\})$ the algebra A with the family $\{p_\alpha\}$ fixed by seminormes $\{p_\alpha\} \in P(A)$.

Given $(A, \{p_\alpha\})$ for each α we denote with N_α the null subspace of p_α , through A_α factor subspace $A|_{N_\alpha}$ and with $\|\cdot\|_\alpha$ we denote the norm on A_α , defined by $\|x + N_\alpha\|_\alpha = p_\alpha(x)$. For each α , we consider the linear canonical map $x \mapsto x_\alpha \equiv x + N_\alpha$ from A to A_α . We denote by 1_α the unital element in A_α and it results that $\|1_\alpha\|_\alpha = 1$ for all α . Michael has obtained the significant result that A is isomorph with a subalgebra of the product of normed algebras $(A_\alpha, \|\cdot\|_\alpha)$.

We know that given the unitary algebra A for any $a \in A$, spectrum of a is defined as:

$\sigma(A; a) = \{\lambda \mid a - \lambda \cdot 1 \text{ is non-invertible}\}$. We denote by $\rho(x) := \sup_{\lambda \in \sigma(A, x)} |\lambda|$ the spectral radius of x .

We now that $\rho(x) = \sup_\alpha \lim_{n \rightarrow \infty} (p_\alpha(x^n))^{1/n}$.

2 Projective systems. Projective limits

Let be $(A_i)_i \in I$ a family of algebras with I increasingly family, i.e for all $i, j \in I \Rightarrow \exists k \in I, \text{ cu } i \leq k, j \leq k$. Let be a family $\{f_{ij}\}_{i,j \in I}$ of morphism of algebras given by:

1. $f_{ij} : A_j \rightarrow A_i$ for all $i, j \in I$ with $i \leq j$
2. $f_{ii} = id_{A_i}, i \in I$
3. $i, j, k \in I, \text{ cu } i \leq j \leq k \Rightarrow f_{ik} = f_{ij} \circ f_{jk}$

The family $\{(A_i, f_{ij})\}_{i,j \in I}$ is call *projective system algebras*. We consider cartesian product $F = \prod_{i \in I} A_i$ and the following subset of F :

$$A = \{x \in (x_i)_{i \in I} \in F \mid x_i = f_{ij}(x_j), \text{ dac@a } i \leq j \in I\}.$$

Theorem 1. *A is a subalgebra of F.*

Proof. We show that A is a subalgebra of F . Let $x, y \in A$, it follows that $x_i + y_i = f_{ij}(x_j + y_j) = f_{ij}(x_j) + f_{ij}(y_j)$. Hence $x + y \in A$. Analogous we show that $\alpha x \in A$, $\forall \alpha \in \mathbf{C}$, $\forall x \in A$.

Let $x, y \in A$, $xy = (x_i y_i)_{i \in I}$, $f_{ij}(x_j y_j) = f_{ij}(x_j) f_{ij}(y_j) = x_i y_i$, $\forall i, j \in I$ with $i \leq j$. Hence $xy \in A$. \square

If each algebra A_i , $i \in I$ have unital element, 1_i and morphisms f_{ij} , with $i \leq j$, $i, j \in I$ keeps unital, then unital of F , $1 = (1_i)_{i \in I}$ we find in subalgebra A of F .

The algebra A defined above is called projective limit algebra of projective system of algebras (A_i, f_{ij}) and to denote through $A = \lim_{\leftarrow} (A_i, f_{ij})$ or $A = \lim_{\leftarrow} A_i$. On the other hand doing a projective system of algebra to define a family $(f_i)_{i \in I}$ of morphism of algebras through $f_i = \pi_i|_A : A \rightarrow A_i$ for all $i \in I$ i.e. considering restrictions to of A projects π_i of F on A_i .

The applications F_i can not to be surjectives.

From the definition of A and definition of applications f_i , it follows that $f_i = f_{ij} \circ f_j$ for any $i, j \in I$ with $i \leq j$.

$$f_{ij}(f_j(x)) = f_{ij}(x_j) = x_i = f_i(x).$$

Definition 1. Let be (A_i, f_{ij}) a projective system of algebras, where A_i for any $i \in I$ is a topological algebra and $f_{ij}, i, j \in I, i \leq j$, continuous morphism of algebras.

The system (A_i, f_{ij}) is called a projective system of topological algebras.

The projective limits A is endowed with initial topology defined by family $(f_i)_{i \in I}$. This topological algebra is named projective limit of topological algebras.

Proof. A projective limit of locally m-convex algebras is an algebra. \square

Lemma 1. Let $A = \lim_{\leftarrow} (A_i, f_{ij})$ a projective limit of topological algebras. Then the family $\{f_i^{-1}(U_i) | U_i \in \mathcal{V}_i, i \in I\}$, where \mathcal{V}_i represents a fundamentally system by neighborhoods of 0 from algebra $A_i, i \in I$ is a fundamentally system by neighborhoods of 0 for A .

Proof. Let $f_i = \pi_i|_A : A \rightarrow A_i$. We have that

$$\bigcap_{j=1}^n \pi_{i_j}^{-1}(U_{i_j}) \text{ implies } \bigcap_{j=1}^n f_{i_j}^{-1}(U_{i_j}), \quad (1)$$

where U_{i_j} belong of a fundamentally system of neighborhoods of 0, from A_{i_j} , is a fundamentally system of neighborhoods of 0 on $\prod_{i \in I} A_i$. Since I is a increasingly set $i \in I$, there exists $i_j \leq i, j = 1, \dots, n$ such that $f_{i_j} = f_{i_j i} \circ f_i$. Hence

$$\bigcap_{j=1}^n f_{i_j}^{-1}(U_{i_j}) = \bigcap_{j=1}^n f_i^{-1} \left(f_{i_j i}^{-1}(U_{i_j}) \right) = \quad (2)$$

$$= f_i^{-1} \left(\bigcap_{j=1}^n f_{i_j i}^{-1}(U_{i_j}) \right) = f_i^{-1}(V_i), \quad (3)$$

where $V_i = \bigcap_{j=1}^n f_{ij}^{-1}(U_{ij})$ is a neighborhood in A_I . There exists $U_i \in \mathcal{V}_i$, such that $U_i \subseteq V_i$ which shows assertions of enunciation. \square

Lemma 2. *Any projective limit of topological algebras $A = \varprojlim A_i$ is a closed subalgebra of topological algebra cartesian product $F = \prod_{i \in I} A_i$. Particularly, A is complete if each $A_i, i \in I$ from topological algebras is complete.*

Proof. Let $x \in \overline{A}$. Then there exists $(x^\alpha)_{\alpha \in J}$, $x^\alpha \in A$, such that $x^\alpha \rightarrow x$ if and only if $x^\alpha - x \rightarrow 0$ if and only if $x_i^\alpha \rightarrow x_i$, for all $i \in I$. From $x^\alpha \in A$ it follows that

$$f_{ij}(x_j^\alpha) = x_i^\alpha, \quad (\forall) i \leq j, \quad i, j \in I. \quad (4)$$

From the continuity of f_{ij} it follows that

$$f_{ij}(x_j) = x_i, \quad (\forall) i \leq j, \quad i, j \in I.$$

Hence $x \in A$. If each $A_i, i \in I$ is complete then the cartesian product A is a complete algebra and how A is a closed space it follows that is complete. \square

Lemma 3. *Let $A = \varprojlim(A_i, f_{ij})$ a projective limit of topological algebra and B is a subalgebra of A . Then*

$$\overline{B} = \bigcap_{i \in I} f_i^{-1} \left(\overline{f_i(B)} \right) = \varprojlim \overline{f_i(B)},$$

where $f_i = \pi_i|_A : A \rightarrow A_i$, $(\forall) i \in I$. Particularly, if B is closed, then

$$B = \varprojlim f_i(B) = \varprojlim \overline{f_i(B)}.$$

Proof. We observe that the family $\{(f_i(B), f_{ij}|_{f_j(B)})\}_{i \in I}$ defines a projective system of topological algebras which it follows that from continuity of f_{ij} with $i \leq j$ and from $f_i = f_{ij} \circ f_j$ for $i \leq j, i, j \in I$.

On the other hand:

$$f_{ij} \left(\overline{f_j(B)} \right) \subseteq \overline{f_{ij}(f_j(B))} = \overline{f_i(B)}.$$

For $i \leq j$ we obtain the family $\left\{ \left(\overline{f_i(B)}, f_{ij}|_{\overline{f_j(B)}} \right) \right\}_{i \in I}$ defines also a projective system of topological algebras.

Immediately from definition it follows that

$$\varprojlim \overline{f_i(B)} = \bigcap_{i \in I} f_i^{-1} \left(\overline{f_i(B)} \right).$$

We show that $\overline{B} = \bigcap_{i \in I} f_i^{-1} \left(\overline{f_i(B)} \right)$.

Let $x \in \overline{B}$. It follows that there exists a generalized sequence of B , $(x^\alpha)_{\alpha \in J}$, such that $x^\alpha \rightarrow x$.

From the continuity of f_i , for all $i \in I$, it results
 $f_i(x^\alpha) \rightarrow f_i(x)$, $(\forall)x \in I \Rightarrow f_i(x) \in \overline{f_i(B)} \Rightarrow$
 $\Rightarrow x \in f_i^{-1} \left(\overline{f_i(B)} \right)$, $(\forall)i \in I$, hence

$$x \in \bigcap_{i \in I} f_i^{-1} \left(\overline{f_i(B)} \right).$$

Conversely, let $x \in \bigcap_{i \in I} f_i^{-1} \left(\overline{f_i(B)} \right)$. It follows that $x \in f_i^{-1} \left(\overline{f_i(B)} \right)$, $(\forall)i \in I$. It follows that $f_i(x) \in \overline{f_i(B)}$, for all $i \in I$, hence

$$x_i \in \overline{f_i(B)}, (\forall)i \in I,$$

it follows that for all $U_i \in \mathcal{V}(x_i)$ we have $U_i \cap f_i(B) \neq \emptyset$ it follows that $f_i^{-1}(U_i) \cap B \neq \emptyset$, hence $x \in \overline{B}$ since $f_i^{-1}(U_i)$ is a fundamental system by neighborhoods of x . On the other hand we have

$$B \subseteq \bigcap_{i \in I} f_i^{-1} (f_i(B)) \subseteq \bigcap_{i \in I} f_i^{-1} \left(\overline{f_i(B)} \right).$$

Then $B \subseteq \lim_{\leftarrow} f_i(B) \subseteq \lim_{\leftarrow} \overline{f_i(B)} = \overline{B}$, which prove last part of lemma. \square

2.1 Arens-Michael Theorem

Theorem 2. (Arens-Michael)

Let be A a locally, m -convex algebra and $\mathcal{V} = (U_i)_{i \in I}$ a fundamental system of neighborhoods of 0 equilibrates, convex, multiplicative and absorbent. We denote with \tilde{A} expanding of A and let be A_i (respective \tilde{A}_i), $i \in I$ normed algebras (Banach) suitable to fundamental system by neighborhoods \mathcal{V} defined above. Then

$$A \hookrightarrow \lim_{\leftarrow} A_i \hookrightarrow \lim_{\leftarrow} \tilde{A}_i = \tilde{A}_i,$$

where \hookrightarrow is injective, topologic morphism of algebras. Particularly, for each locally, m -convex, complete algebra A , with fundamental system by neighborhoods \mathcal{V} , we obtain

$$A = \lim_{\leftarrow} A_i = \lim_{\leftarrow} \tilde{A}_i,$$

where \Rightarrow signifies topological isomorphism of algebras (surjective morphism).

Proof. Let be $(p_i)_{i \in I}$ a increasing family of seminorms associated of \mathcal{V} . Then $A_i = A/N_i = \{x + N_i | x \in A\} = \{x_i\}, i \in I$ where $N_i = p_i^{-1}(0)$, $x_i = x + N_i, i \in I$. Let be $a \in A, x \in N_i$. Then $p_i(ax) \leq p_i(a) \cdot p_i(x)$. Since $p_i(x) = 0$ it follows that $p_i(ax) = 0$. Therefore, $ax \in N_i$. It follows that N_i is an ideal. Then A/N_i is an algebra.

We define $\|x_i\|_i = p_i(x)$ which is obviously norm on A_i . Let $f_{ij} : A_j \rightarrow A_i, \forall i, j \in I, j \geq i$, given:

$$f_{ij}(x + N_j) = x + N_i.$$

Obviously, f_{ij} is a morphism of algebras. Let:

$$(1) \quad f_{ij}((x_1 + N_j)(x_2 + N_j)) = f_{ik}(x_1 x_2 + N_j) = x_1 x_2 + N_i = \\ = (x_1 + N_i)(x_2 + N_i) = f_{ij}(x_1 + N_j) f_{ij}(x_2 + N_j)$$

We have that $\|f_{ij}(x + N_j)\|_i = p_i(x) \leq p_j(x) = \|x + N_i\|_j$; it follows that f_{ij} continuous. We have:

$$(2) \quad f_{ii}(x + N_i) = x + N_i.$$

Let $i \leq j \leq k$. Then

$$(3) \quad f_{ik} = f_{ij} \circ f_{jk}(x + N_k) = f_{ij}(x + N_j) = x + N_i = f_{ik}(x + N_k), \\ \text{hence } f_{ik} = f_{ij} \circ f_{jk}, \text{ for all } i \leq j \leq k, i, j, k \in I.$$

Therefore, from relations (1), (2), (3) the family $\{(A_i, f_{ij})\}$ form a projective system of normed algebras.

Since $(A_i)_{i \in I}$ (respective $(\tilde{A}_i)_{i \in I}$) is a family of normed algebras (respective Banach) and form a projective system of normed algebras it follows that from above propositions that exists $\lim_{\leftarrow} A_i$ (respectively $\lim_{\leftarrow} \tilde{A}_i$) and is a locally m -convex algebra.

Considering locally m -convex algebras $\lim_{\leftarrow} A_i$ and $\lim_{\leftarrow} \tilde{A}_i$, we define the following application:

$$\varphi : A \rightarrow \lim_{\leftarrow} A_i$$

through

$$\varphi(x) = (\varphi_i(x))_{i \in I} = (x_i)_{i \in I}$$

where $\varphi_i(x) = x + N_i = x + \text{Ker}(p_i) = x_i, i \in I$.

To show that φ is well defined to observe that $\varphi_i = f_{ij} \circ \varphi_j$

Indeed, $f_{ij}(\varphi_j(x)) = \varphi_i(x)$. It follows that $\varphi(x) \in \lim_{\leftarrow} A_i$. It is obviously that φ is a morphism of algebras. From $\varphi(u) = 0$ it follows that $(\varphi_i(x))_{i \in I} = 0$ hence $\varphi_i(x) = 0, i \in I$. Hence $p_i(x) = 0, i \in I$. Therefore, $x = 0$ (A algebra separate) and so φ is a injective morphism, hence isomorphic of algebras.

We prove now that φ is topological isomorphism.

We have $f_i \circ \varphi_i = \varphi_i$, for all $i \in I$.

Indeed, $(f_i \circ \varphi)(x) = f_i(\varphi(x)) = f_i(\varphi_i(x)_{i \in I}) = \varphi_i(x)$. Since f_i and φ_i are continue functions $i \in I$ it follows that φ is continuous.

The inverse functions $\varphi^{-1} : \lim_{\leftarrow} A_i \rightarrow A$ is also continuous. Indeed if $U_i \in \mathcal{V}$ then

$$V = \left(\prod_{j \in I} V_j \right) \cap \varphi(A),$$

with $U_i = \varphi_i(\frac{1}{2}U_i)$ and $V_j = A_j$, for any $j \in V, j \neq i$ is a neighborhoods of 0 in $\varphi(A)$ with properties that $V \subseteq \varphi(U_i)$, which means $\varphi^{-1}(V) \subseteq U_i$ and hence φ^{-1} is continuous.

We verify that $V \subseteq \varphi(U_i)$. Let $y \in V \Rightarrow y \in \prod_{j \in J} V_j$ and $y \in \varphi(A)$,

it follows that there exists $x \in A$ with $y = \varphi(x)$ and $\varphi_i(x) = \varphi_i(\frac{1}{2}z)$, with $z \in U_i$.

$$\begin{aligned} \text{Hence } p_i(x) &= p_i\left(\frac{1}{2}z\right) = \frac{1}{2}p_i(z) \leq \frac{1}{2} < 1 \Rightarrow \\ &\Rightarrow x \in U_i \Rightarrow y = \varphi(x) \text{ with } x \in U_i \Rightarrow y = \varphi(x) \in \varphi(U_i) \Rightarrow \\ &\Rightarrow V \subseteq \varphi(U_i) \Rightarrow \varphi^{-1}(V) \subseteq U_i. \end{aligned}$$

Therefore, φ is surjective, topologic morphism of algebras of A to into $\lim_{\leftarrow} A_i$.

We have canonical injections $\theta_i : A_i \rightarrow \tilde{A}_i, i \in I$ which are algebraical and topological isomorphisms and commutes with the maps f_{ij} and with their extensions $\tilde{f}_{ij} : \tilde{A} \rightarrow \tilde{A}_i$, with $i \leq j$.

We obtain:

$$\theta : \lim_{\leftarrow} A_i \rightarrow \lim_{\leftarrow} \tilde{A}_i$$

defined through $\theta(x) = (\theta_i(x_i)), i \in I$.

$$\tilde{f}_{ij}(\theta_j(x_j)) = \tilde{f}_{ij}(x_j) = f_{ij}(x_j) = x_i = \theta_i(x_i)$$

Isomorphism θ is topologic too, which it follows immediately from the definitions of algebraical topologies.

On the other hand, since

$$f_i \circ \varphi = \varphi_i, (\forall) i \in I, \quad \varphi_i : A \rightarrow A_i = A / \text{Ker } \varphi_i$$

we have:

$$f_i(\varphi(A)) = \varphi_i(A) = A_i, i \in I$$

and then from above lema and from conclusions for φ we obtain

$$A \subseteq \overline{A} = \overline{\varphi(A)} = \lim_{\leftarrow} \overline{f_i(\varphi(A))} = \lim_{\leftarrow} A_i = \lim_{\leftarrow} \tilde{A}_i.$$

Since the last space is complete it follows that from above lemma $\tilde{A} = \overline{A} = \lim_{\leftarrow} \overline{A}_i = \lim_{\leftarrow} \tilde{A}$ where equality represents isomorphisms of studied algebras above.

Therefore from θ is a topological isomorphism the proof is end. \square

2.2 Applications of Arens-Michael theorem

Theorem 3. Let be A a locally, m -convex and complete algebra and $A = \varprojlim A_i$.

- 1) The algebra A has unital element if and only if \tilde{A}_i has unital element for all $i \in I$.
- 2) An element $x \in A$ is invertible if and only if $\varphi_i(x)$ is invertible in \tilde{A}_i for any $i \in I$.

Proof. We suppose $1 = (1_i) \in \prod_{i \in I} \tilde{A}_i$, with 1_i unital element in \tilde{A}_i for $i \in I$.

Since $A_i = \varphi_i(A)$, if $x_i = \varphi_i(x) \in A_i$, then

$$\begin{aligned} x_i \tilde{f}_{ij}(1_j) &= \varphi_i(x) \tilde{f}_{ij}(1_j) = \tilde{f}_{ij}(\varphi_j(x)) \tilde{f}_{ij}(1_j) = \tilde{f}_{ij}(\varphi_j(x) 1_j) = \\ &= \tilde{f}_{ij}(\varphi_j(x)) = \varphi_i(x) = x_i \end{aligned}$$

for any $i \leq j$ and similarly for left multiplication with $\tilde{f}_{ij}(1_j)$, hence $\tilde{f}_{ij}(1_j)$ is a unital for A_i , hence also for $\tilde{A}_i = \overline{A}_i$. Then it follows that $\tilde{f}_{ij}(1_j) = 1_i$ for any $i \leq j$ from I , hence $1 = (1_i)_{i \in I} \in \varprojlim \tilde{A}_i = A$.

Verify that 1 is unital element of A .

We prove (2). If $x = (x_i)_{i \in I} \in A = \varprojlim A_i$, how x_i is invertible of \tilde{A}_i for any $i \in I$, there exist $y = (y_i)_{i \in I} \in \prod_{i \in I} \tilde{A}_i$ such that:

$$x_i \cdot y_i = y_i \cdot x_i = 1_i,$$

where from (1) we know that $(1_i)_{i \in I} = 1$ is a unital element of A .

Now for $i \leq j$ from I , we obtain:

$x_i \cdot \tilde{f}_{ij}(y_j) = \tilde{f}_{ij}(x_j) \cdot \tilde{f}_{ij}(y_j) = \tilde{f}_{ij}(x_j \cdot y_j) =$
 $= \tilde{f}_{ij}(1_j) = 1_i = \tilde{f}_{ij}(y_j) \cdot x_i$, which means that $\tilde{f}_{ij}(y_j)$ is inverse of x_i in \tilde{A}_i and then we deduce $\tilde{f}_{ij}(y_j) = y_i$, for $i \leq j$ from I .

Hence $y = (y_i)_{i \in I} \in \varprojlim A_i$. From above we deduce that y is inverse of x in A . \square

Corollary 1. Let be A a locally, m -convex and complete algebra and $x \in A$. Then:

$$\sigma(A, x) = \bigcup_{i \in I} \sigma(A, x_i),$$

$$\rho(x) = \sup_{i \in I} \rho(x_i) = \sup_{i \in I} \lim_{n \rightarrow \infty} (p_i(x^n))^{\frac{1}{n}}.$$

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