MATHEMATISCHES FORSCHUNGSINSTITUT OBERWOLFACH

Tagungsbericht 46/1996

Positivity in Lie Theory

08.12 - 14.12. 1996

The meeting has been organized by Joachim Hilgert (Clausthal), Jimmie D. Lawson (Baton Rouge) and Ernest B. Vinberg (Moscow). The topics treated can be collected into the following groups:

- Harmonic Analysis
- Representation Theory
- Structure Theory of Lie Semigroups
- Geometric Control Theory
- Structure Theory of Reductive Algebraic Groups
- Invariant Complex Analysis
- Probability Theory

The common feature in the various contributions was the use of some concept of positivity. This could be for instance

- subsemigroups of Lie groups
- semigroups occurring as closures of Lie groups
- partial orders on (homogeneous) manifolds
- (homogeneous) convex cones

A particularly active field of research in recent years have been the applications of positivity concepts in the geometric construction of Hilbert spaces of holomorphic functions on which one obtains natural unitary representations. Other remarkable results deal with invariant domains of holomorphy in non-compact complex manifolds, the description of the control set structure of certain model systems on flag manifolds, or a generalization of total positivity to general real reductive groups.

The meeting consisted of 14 morning lectures and several informal topical afternoon sessions with short presentations designed to start up discussions.

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VORTRAGSAUSZÜGE (in chronologischer Ordnung)

Monday, Dec. 9:

W. BERTRAM: *Jordan Algebras - an Introduction*

M. Koecher and E.B. Vinberg have established a bijective correspondence between Euclidean Jordan algebras and a class of geometric objects called *symmetric cones.* We raise the question wether there is a correspondence between *all* Jordan algebras and some bigger class of geometric objects - similar to the correspondence of Lie algebras and with Lie groups. The main topic of the lecture is to describe this class of geometric objects: they are *prehomogeneous symmetric spaces* having some additional property (cf. article "Jordan algebras and Conformal geometry" in the problem-collection to this conference). This set-up is very convenient to describe some features of basic structure theory of Jordan algebras such as *quadratic representation, Jordan inverse, structure group, conformal group, Cartan-subspaces* and *Jordan determinant.*

J. FARAUT: *Riesz Integrals on Ordered Symmetric Spaces*

We construct a causal elementary solution of an hyperbolic invariant differential operator on an ordered symmetric space by using Riesz integrals. An *ordered symmetric space* is a semi-simple symmetric space $M = G/H$ equipped with an invariant global causal structre. Let Ω be a symmetric cone in a Euclidean Jordan algebra V, $H = G(\Omega)$ the group of linear automorphisms of Ω, $G = \mathrm{Aut}(T_\Omega)$ the group of holomorphic automorphisms of the tube $T_\Omega = V + i\Omega$. Then $M = G/H$ is an ordered symmetric space *of Cayley type.* Let Δ be the Jordan determinant of V. The set $\{(x,y) \in V \times V |\, \Delta(x-y) \neq 0\}$ can be seen as a dense open set in M. The operator

$$D = \Delta(x-y)^{1+\frac{n}{r}}\Delta(\frac{\partial}{\partial x})\Delta(\frac{\partial}{\partial y})\Delta(x-y)^{1-\frac{n}{r}}$$

($n = \dim V$, $r = \mathrm{rank} V$) is invariant and hyperbolic. Following Riesz' method one defines the Riesz integral $I^\alpha f$ of a function f. It converges for Re α large enough and has an analytic continuation as an entire function of α. For $\alpha = 1$, I^α is a causal elementary solution of the hyperbolic invariant differential operator D.

J.-L. CLERC: *Unitary Highest Weight Modules*

For G/K a Hermitian symmetric space, Harish Chandra introduced a family of holomorphic representations defined on holomorphic sections of bundles of G/K. Using the invariant measure on G/K, it is possible to define a unitary structure, and the action of G is unitary and irreducible on the L^2-sections. One obtains the holomorphic discrete series. However, there might be no L^2-holomorphic sections; then one looks for other Hilbert space structures invariant under the G-action. These representations (=unitary highest weight modules) were classified (by Jakobsen / Enright-Howe-Wallach '83), mostly using algebraic arguments.

For tube type domains, we present a different approach to this problem. Because the Hilbert spaces consist of holomorphic functions, they admit *reproducing kernels*, and these kernels are a priori determined by their invariance properties w.r.t. G. One has to check their positive-definiteness.

Using extension of a unitary highest weight representation to holomorphic semigroups (a result due to G. Olshanski), we are able to show that the unitarity is equivalent to the existence of an (operator valued) measure in the closure of the cone Ω, satisfying certain invariance conditions together with a Laplace transform type condition. This leads to a realization of the corresponding Hilbert space.

It is also possible, at least in some cases, to answer the existence question of such a measure (further results have been obtained by J.Hilgert and K.H. Neeb).

Topical Session HARMONIC ANALYSIS AND JORDAN ALGEBRAS with contributions by P. GRACZYK, M. CHADLI, F. BETTEN and M. PEVSNER

Tuesday, Dec. 10:

B. ØRSTED: *Unitary Highest Weight Representations*

In this lecture we gave in detail some of the background for the formulation of the problem of finding the unitary highest weight modules for a real simple Lie algebra. In particular we discussed the approach by

Harish-Chandra (1955) who first constructed global representations in this class, namely the *holomorphic discrete series* over a Hermitian symmetric space. We also gave the dual infinitesimal analogue as simple quotients in Verma modules and formulated the problem as that of positivity of the canonical Hermitian form here. We indicated the qualitative aspects of the answer (as also reported on in the lecture by J.L. Clerc) and finished by the recent results of J. Hilgert and K.H. Neeb, who have given an analytical reformulation of the problem in terms of an operator-valued gamma function, and have solved this problem for a certain class of lowest K-types.

J. HILGERT: *Compression Semigroups*

Let G be a group and M a set on which G acts. To any set $\Omega \subset M$ one associates a group $G(\Omega) = \{g \in G | g \cdot \Omega = \Omega\}$ and a semigroup $S(\Omega) = \{g \in G | g \cdot \Omega \subset \Omega\}$. This semigroup is called the *compression semigroup of* Ω. Such semigroups show up in the study of holomorphic extensions of unitary highest weight representations, harmonic analysis on causal symmetric spaces, and in control theory. Combining methods from representation theory (projective embeddings) and control theory (invariant control sets) one can show that for causal symmetric spaces G/H and open H-orbits in a naturally associated maximal parabolic subgroup of G the corresponding compression semigroup is a *maximal* semigroup.

Z.J. JUREK: *Semigroup Methods in Probability*

For a Banach space E let $\mathcal{P}(E)$ denote the space of probability measures on E. For $\mu \in \mathcal{P}(E)$ we define its *decomposability semigroup* $\mathbb{D}(\mu) := \{A \in End(E) : \exists \nu_A \in \mathcal{P}(E) : \mu = A\mu * \nu_A\}$. (Here: $*$ = convolution of measures, $A\mu = \mu A^{-1}$ = image of measure μ under mapping operator A.) The semigroup $\mathbb{D}(\mu)$ contains the group of units which is exactly equal to $\mathbb{A}(\mu) = \{A \in \mathbb{D}(\mu) : \exists a \in E : \mu = A\mu * \delta_a\}$ where δ_a is the point-mass measure at point a. For μ on $\mathbb{R}^d$ such that supp$\mu \not\subset (d-1)$-hyperplane, $\mathbb{A}(\mu)$ is a compact subgroup of $Aut(\mathbb{R}^d)$. We show that each compact subgroup of $\mathrm{Gl}(\mathbb{R}, d)$ is isomorphic to $\mathbb{A}(\mu)$ for a full measure μ on $\mathbb{R}^{d^2}$.

(M. Meerschaert and J.A. Veeh after E. Bedford and J. Dadok).

Introducing in $\mathcal{S} := \mathcal{P}(E) \times End(E)$ an operation "$\square$" by the formula $(\mu, A) \square (\nu, B) := (\mu * A\nu, AB)$ and taking weak topology on $\mathcal{P}(E)$ and operator norm topology on $End(E)$, we get a topological semigroup with a unit (δ_0, I). Each one-parameter semigroup $T(t)$ in $\mathcal{S}$ is of the form

$$(1) \qquad T(t) = \mathcal{L}\Big(\int_{(0_\nu, t]} e^{sQ} dY(s,w), e^{tQ}\Big), \quad t \geq 0,$$

where $\mathcal{L}(\cdot)$ denotes the probability distributions of random integral with respect to Lévy process Y.

As open problems we state the following:

(a) Is any compact *subsemigroup* in $End(\mathbb{R}^d)$ isomorphic to the decomposability semigroup $\mathbb{D}(\mu)$, for some probability measure μ?

(b) Characterize all pairs of measures ρ_1 and ρ_2 (for instance on the real line) such that

$$(2) \qquad \forall t \in \mathbb{R}: \quad \int_{-\infty}^{\infty} e^{tx} \rho_1(dx) \cdot \int_{-\infty}^{\infty} e^{itx} \rho_2(dx) = 1$$

Topical Session LIE SEMIGROUPS AND PROBABILITY with contributions by W. RUPPERT, E.B. VINBERG, V. GICHEV and W. JAWORSKI,

Wednesday, Dec. 11:

K.H. HOFMANN: *A Survey on the Structure of the Exponential Function*

For a real Liegroup G, the exponential function $\exp : \mathfrak{g} \to G$ fails in general to be surjective. It is perhaps surprising that after more than 100 years of research on Lie groups, general necessary and sufficient conditions for the surjectivity of the exponential function appear to be lacking. The status of the problem is surveyed. Some statements in the literature require reconsideration, the early history of the structure of exp is the first part of the survey. The second concerns a description of Lie groups G for which $\overline{\exp \mathfrak{g}} = G$. This situation is quite well understood. The discussion here requires a refocusing on Cartan subgroups of G (of course in the absence of semisimplicity, at the level of generality we require). We call those groups which satisfy $\exp \mathfrak{g} = G$ *exponential* and collect those pieces of information available on them today. A section on the complete characterization of (reduced) subsemigroups $S \subset G$ satisfying $\exp(\mathcal{L}(S)) = S$ concludes the survey.

V. JURDJEVIC: *Kovalevska Integral on Lie Groups*

There is a close connection between the study of Euler in 1765 concerning the solutions of $\frac{dx}{\sqrt{P(x)}} \pm \frac{dy}{\sqrt{P(y)}} = 0$, where P is a general fourth degree polynomial, and the integration technique used by Kowalevska in 1889 in the resolution of Hamiltonian equations concerning the motions of the heavy top. A proper interpretation of a Theorem of Kirchhoff of 1885 concerning the equilibria configurations of an elastic rod leads to a class of variational problems on the group of motions of $\mathbb{R}^3$ and its non-Euclidean neighbors $\mathrm{SO}_4(\mathbb{R})$ and $\mathrm{SO}(3,1)$ resulting in the Hamiltonian function H resembling the Hamiltonian of the heavy top, i.e.

$$H = \frac{1}{2}\left(\frac{H_1^2}{c_1} + \frac{H_2^2}{c_2} + \frac{H_3^2}{c_3}\right) + h_1.$$

For each of these groups, the remarkable relation $c_1 = c_2 = 2c_3$ of Kowalewska leads to an extra integral of motion

$$J_4^2 = \left(\frac{1}{4}(H_1^2 - H_2^2) - h_1 - k\right)^2 + \left(\frac{1}{2}H_1 H_2 - h_2\right)^2,$$

where $k = 0, 1, -1$ corresponds to the curvature of the underlying symmetric space $\mathbb{R}^3, S^3$ and H^3 (Minkowski hyperboloid).

The integration procedure leads to Kowalevska relations

$$R^2(x,y) + (x-y)^2 R_1 = P(x)P(y)$$

for two forms R and R_1 of degree four, P a fourth degree polynomial such that $R(x,x) = P(x)$. Apart from the resolution of the Hamiltonian equations on Abelian varieties, the above formula may also be used to recover Euler's results of 1765 mentioned earlier, and by extension also provide proofs for A. Weil's addition formulas (1954) for the groups $\mathcal{C} \cup \Gamma$ with $\mathcal{C} = \{(x,u) : u^2 = P(x)\}$ and $\Gamma = \{(\xi,\eta) : \eta^2 = 4\xi^3 - g_2\xi - g_3\}$ with g_2 and g_3 the invariants of $\mathcal{C}$, i.e. $g_2 = AE - BD + 3C^2$, $g_3 = ACE + 2BCD - AD^2 - B^2E - C^3$ whenever $P = A + 4Bx + 6Cx^2 + 4Dx^3 + Ex^4$.

K.-H. NEEB: *Domains of Holomorphy via Representation Theory*

Given a group G acting by holomorphic maps on a Stein manifold, the fundamental questions in complex analysis are to characterize G-invariant domains of holomorphy (Stein subdomains) and the G-invariant plurisubharmonic functions. In this lecture we explain how these problems can be approached via representation theoretic methods. The manifolds we consider are of the type $G \cdot \exp(iW) \subset G_{\mathbb{C}}$, where G is a real Lie group, $G_{\mathbb{C}}$ its complexification, and $W \subset \mathrm{Lie}(G)$ an open invariant cone consisting of elliptic elements. For a domain $D = G \cdot \exp(iD_h)$ in such a semigroup, which is G-biinvariant, i.e. invariant under left and right multiplication, one can show that D is Stein iff D_h is convex, and that biinvariant plurisubharmonic functions on D correspond to invariant convex functions on D_h. Even though the proof of these results draws heavily from representation theory, these results can be used to get a complete abstract description of all biinvariant Hilbert subspaces of $\mathcal{O}(D)$ on which $G \times G$ acts unitarily as direct integrals of highest weight representations.

Thursday, Dec. 12:

W. KLIEMANN: *On the Spectrum of Control Systems*

The Lyapunov spectrum of a control system plays a major role in the robust design of systems, in the construction of stabilizing feedbacks, in the persistence analysis of dynamical systems, etc. The main message of this presentation is that the complex Lyaponov spectrum of bilinear systems on vector bundles can be expressed (almost always!) via the Floquet spectrum of the associated semigroup. Let $\dot{x} = X_0(x) + \sum_{i=1}^{m} u_i(t)X_i(x)$ be a smooth bilinear control system on a vector bundle $\pi : F \to M$, where M is (compact), C^∞, Riemannian. Over each main control set $D \subset M$ of the base flow, let $\mathbb{P}D_i$ be the main control sets in the projective bundle $\mathbb{P}\pi : \mathbb{P}F \to M$. Define $\Sigma_{Fl}(\mathbb{P}\mathcal{D}_i)$ as the Floquet spectrum of the inner pairs in the lift $\mathbb{P}\mathcal{D}_i \subset \mathcal{U} \times \mathbb{P}F$, where $\mathcal{U}$ is the set of control functions with values in the compact, convex control range $U \subset \mathbb{R}^m$ with $0 \in \text{int}U$. The *inner pair condition* is the proper nonlinear generalization of the requirement that the associated semigroup have nonvoid interior in the systems group. Then $\Sigma_{Fl}(X,U) = \cup_{D \text{ is mcs in } M} \cup_{\mathbb{P}D_i \subset \mathbb{P}F} \Sigma_{Fl}(\mathbb{P}D_i)$ consists of bounded intervals and agrees with the Floquet spectrum of the system semigroups (its inner elements). Obviously, $\Sigma_{Fl}(X,U)$ is an inner approximation of the Lyaponov spectrum $\Sigma_{Ly}(X,U)$. Next we contruct an outer approximation via the chain recurrent components of the control flow and the projective flow (i.e. on the chain control sets in M and and $\mathbb{P}F$). This leads to the Morse spectrum via limits of finite time controlled chains and their chain exponents. One obtains that $\Sigma_{Mo}(X,U) = \cup_{E \text{ is ccs in } M} \cup_{\mathbb{P}E_i \subset \mathbb{P}F} \Sigma_{Mo}(\mathbb{P}E_i)$ consists of bounded intervals and contains the Lyapunov spectrum. Now embed the control system into a family by considering varying control ranges $U^\rho = \rho \circ U$, $\rho \geq 0$. Under a slightly stronger inner pair condition on the chain recurrent components on $\mathcal{U} \times \mathbb{P}F$ one obtains that $\text{cl}\Sigma_{Fl}(\mathbb{P}D_i^\rho) = \Sigma_{Mo}(\text{cl}\mathbb{P}D_i^\rho)$ for all ρ except for at most countably many exceptional points. Hence $\text{cl}\Sigma_{Fl}(X,U^\rho) = \Sigma_{Ly}(X,U^\rho) = \Sigma_{Mo}(X,U^\rho)$ at the ρ-continuity points, and $\text{cl}\Sigma_{Fl}(X,U^\rho)$ is determined by the systems semigroup.

L.A.B. SAN MARTIN: *Homogeneous Spaces Admitting Transitive Semigroups*

Let G be a semi-simple Lie group with finite center, $L \subset G$ a subsemigroup with $\text{int}S \neq \emptyset$. The problem is to decide whether S is transitive on G/L, that is, whether

$$Sx := \{gx : g \in S\} = G/L$$

for all $x \in G/L$. This problem is approached through the action of S on the flag manifolds of G, which are homogeneous spaces G/P with P a parabolic subgroup. Associated with S there is a special flag manifold, denoted $B(S)$. In the flag there is a subset $C \subset B(S)$ which is S-invariant (invariant control set), and such that $h^k(C)$ converges to a point as $k \to \infty$. Here $h \in \text{int}(S)$ is a regular real element. It is proved that the following conditions are necessary in order that S is transitive on G/L:

a) The action of l on $B(S)$ is minimal.

b) L admits a contractive sequence with respect to $B(S)$.

These conditions are also sufficient in case S is assumed to be the compression semigroup of C (i.e., $S = \{g \in G : gC \subset C\}$). A connected subgroup L satisfies these conditions only if it is reductive and (exactly) transitive on $B(S)$. Moreover its semi-simple component, say E, is also transitive on $B(S)$, which turns out to be a flag manifold of E. Also, it is shown that L is discrete if G/L is compact and admits a transitive semigroup.

M. PUTCHA: *Reductive Monoids*

A *reductive monoid* M is an irreducible affine variety with a polynomially defined associative multiplication and a reductive unit group G. Such monoids are obtained as Zariski closures of reductive groups. We will discuss various decompositions of a reductive monoid. We begin by discussing the $G \times G$-orbits (J-classes), leading to the concept of a cross-section lattice. Next we consider the $B \times B$-orbits, Renner monoid and the analogue of the Bruhat-Chevalley order. Finally we will consider a decomposition of M related to the conjugacy classes of M. This leads to a decomposition of the nilpotent variety of M into its irreducible components.

Topical Session REPRESENTATION THEORY with contributions by B. KRÖTZ, M. NAZAROV, V. MOLCHANOV and W. LISIECKI

Topical Session CONTROL THEORY I with contributions by F. COLONIUS, D. MITTENHUBER, M. ZELIKIN and V. GICHEV

Friday, Dec. 13:

G. LUSZTIG: *Total Positivity in Lie Groups*

Let G be the group of real points of a semisimple, simply connected algebraic group over $\mathbb{C}$ with a fixed real split structure. We fix Chevalley generators e_i, f_i, h_i $(i \in I)$ for the Lie algebra of G. We define $G_{\geq 0}$

to be the submonoid of G generated by $\exp(ae_i)$, $\exp(af_i)$ ($a \in R_{\geq 0}$, $i \in I$) and by the identity component of the real torus T corresponding to $\sum_i \mathbb{R}h_i$. Then $G_{\geq 0}$ is a closed subset of G which equals the closure of its interior $G_{>0}$ (which is again a semigroup). For Sl_n, these semigroups are classically known as "totally positive matrices". The open semigroup $G_{>0}$ is a connected component of the intersection of two big double cosets with respect to to opposed Borel subgroups. If $\mathcal{B}$ is the real flag manifold of G, one can define a closed subset $\mathcal{B}_{\geq 0}$ as follows. We choose a Borel subgroup B containing T and define $\mathcal{B}_{\geq 0}$ as the closure of $\{gBg^{-1} | g \in G_{\geq 0}\}$; this set is independent of the choice of B. It is equal to the closure of its interior $B_{>0}$. For any $g \in G$, the set $\{B \in \mathcal{B}_{\geq 0} | g \in B\}$ is non-empty (and probably contractible). The proofs of these results rely on the positivity properties of canonical bases in envoloping algebras, hence are non-elementary since they involve the decomposition theorem for perverse sheaves.

Topical Session ALGEBRAIC GROUPS with contributions by K. RIETSCH, M. NAZAROV, L. RENNER and D. BURDE

Topical Session CONTROL THEORY II with contributions by O. DO ROCIO and A. GUTS

Y. NERETIN: *Compression of Angles in Symmetric Spaces*

Consider the space $I_{p,q} = U(p,q)/(U(p) \times U(q))$, i.e. the space of $p \times q$-matrices Z such that $||Z|| < 1$. Let $Z, U \in I_{p,q}$. Then the *complex distance* $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \ldots$ is the set of singular values of the matrix

$$(1 - Z^*Z)^{-1/2}(1 - Z^*U)(1 - U^*U)^{-1/2}.$$

Krein-Schmullian's *generalized fractional linear map* is a map having the form

$$(*) \qquad \tau : Z \mapsto K + LZ(1 - NZ)^{-1}M,$$

where $S = \begin{pmatrix} K & L \\ M & N \end{pmatrix}$ is a $(p+s) \times (q+r)$-matrix such that

$$||S|| \leq 1, \quad ||K|| < 1, \quad ||N|| < 1.$$

The formula $(*)$ defines the map $I_{r,s} \to I_{p,q}$.

Theorem. Let τ be a generalized fractional-linear map. Let $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \dots$ be the complex distance between Z_1 and Z_2, and let $\mu_1 \geq \mu_2 \geq \mu_3 \geq \dots$ be the complex distance between $\tau(Z_1)$ and $\tau(Z_2)$. Then

$$\lambda_1 \geq \mu_1, \quad \lambda_2 \geq \mu_2, \quad \lambda_3 \geq \mu_3, \dots$$

Topical Session COMPLEX ANALYSIS with contributions by G. FELS and R. BREMIGAN

Berichterstatter: W. Bertram und J. Hilgert

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