PhD in Information Technology and Electrical Engineering
Università degli Studi di Napoli Federico II

PhD Student: Marco Boddi

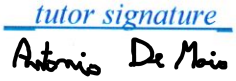
Cycle: XXXVII

Training and Research Activities Report

Academic year: 2022-23 - PhD Year: Second


student signature

Tutor: prof. Antonio De Maio


tutor signature

Co-Tutor:

Date: October 21, 2023

1. Information:

- **PhD student: Marco Boddi** **PhD Cycle: XXXVII**
- **DR number: 995996**
- **Date of birth: 03/04/1984**
- **Master Science degree: Telecommunications Engineering, University of Pise**
- **Scholarship type: ad-hoc agreement between UniNa and the Presidency of the Council of Ministers if Italy**
- **Tutor: Prof. Antonio De Maio**

2. Study and training activities:

Activity	Type[1]	Hours	Credits	Dates	Organizer	Certificate[2]
"Simulation of Radar Sea Clutter", from the 2022 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	14 / 11 / 2022	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Rosenberg	To be released at the end of the 2022-2023 Lecturer Series
"Gravity-Modeling Considerations in High-Integrity Inertial Systems", from the 2022 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	30 / 11 / 2022	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Braasch	To be released at the end of the 2022-2023 Lecturer Series
"Radar Technology and Sustainability: How to Conjugate Innovation and Social Duties", from the 2022 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	05 / 12 / 2022	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Farina	To be released at the end of the 2022-2023 Lecturer Series
"Cognitive Radars", from the 2022 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	14 / 12 / 2022	IEEE AESS (Aerospace and	To be released at the end of the 2022-2023

					Electronic Systems Society), lecturer Greco	Lecturer Series
"Publishing Open Access IEEE Journal Articles under the Care Crui Agreement in Italy"	Seminar	1	0.2	09 / 11 / 2022	IEEE – the Institute of Electrical and Electronics Engineers, lecturer Lukacs	Y
"Waveform Design for Spectral Coexistence between Radar and Communication Systems"	Seminar	1	0.2	24 / 11 / 2022	IEEE-ISAC (Integrated Sensing and Communications), lecturer De Maio	Y
"Data mining the output of quantum simulators – from critical behavior to algorithmic complexity", from the Quantum Science Technology seminars' series.	Seminar	1	0.2	11 / 11 / 2022	Unina and CNR (Consiglio Nazionale delle Ricerce), Lecturer Dalmonte	To be released
"Connecting the dots: Investigating an APT campaign using Spunk"	Seminar	2	0.4	11 / 11 / 2022	Unina DIETI, Lecturer Forzieri	To be released
"Cybercrime and Information Warfare: National and International Actors"	Seminar	2	0.4	18 / 11 / 2022	Unina DIETI, Lecturer Paganini	To be released
"From Cyber Situational Awareness to Adaptive Cyber Defense: Leveling the Cyber Playing Field"	Seminar	2	0.4	13 / 12 / 2022	Unina DIETI, Lecturer Albanese	To be released
"Threat Hunting and Incident Response"	Seminar	2	0.4	13 / 12 / 2022	Unina DIETI, Lecturer Albanese	To be released
Study of the following papers:	Research		3	Nov-Dec 2022		

• "Radar Waveform Design in a Spectrally Crowded Environment Via Nonconvex Quadratic Optimization" (A. Aubry, A. De Maio, M. Piezzo, A. Farina); • "A new radar waveform design algorithm with improved feasibility for spectral coexistence" (A. Aubry, A. De Maio, Y. Huang, M. Piezzo, A. Farina); • "DOA Estimation for UCA in the Presence of Mutual Coupling via Error Model Equivalence" (W. Hu, Q. Wang); • "Direction Finding in the Presence of Mutual Coupling" (B. Friedlander, A. J. Weiss) • Software modelling and simulations for managing mutual coupling in antenna arrays and joint array calibration and signal detection/estimation.						
Initial work for a research paper on a novel procedure for the iterative estimation of the Direction of Arrival of incoming signals in a receiving array affected by antenna coupling. Submission of the paper abstract for the NATO Radar Research Specialists' Meeting on	Research		2	Dec 2022		

"New Mathematics for Multi-Dimensional Radar Systems						
On the challenges and impact of Artificial Intelligence in the Insurance domain	Course	12	3	Nov 2022, exam taken on 15 / 01 / 2023	Dieti / Unina, Lecturer Ricciardi Celsi	Y
Industry 4.0 Fundamentals in Bosch Applications	Seminar	10	2	23-26 / 01 / 2023	Dausy / University of Bari and Bosch, Lecturers Bruni, Dotoli	Y
Preparation and submission of a research paper to the conference NATO RSM-319 (Research Specialist Meeting) on "New Mathematics for Multidimensional Radar Systems": • M. Boddi, M. Rosamilia, A. Aubry, A. De Maio, "Iterative Direction-of-Arrival Estimation for a Uniform Circular Array in the Presence of Mutual Coupling". Participation to the conference NATO-RSM-319 (Research Specialist Meeting) on "New Mathematics for Multidimensional Radar Systems", ICMS (International Centre for Mathematical Sciences) Edinburgh 21-23.02.2023. Presentation on the paper submitted.	Research		7	Jan-Feb 2023		

Study of the following papers: • J. Dai, X. Bao, N. Hu, C. Chang, W. Xu, "A Recursive RARE Algorithm for DOA Estimation with Unknown Mutual Coupling"; • M. Lin, L. Yang, "Blind Calibration and DOA Estimation with Uniform Circular Arrays in the Presence of Mutual Coupling"; • W. Hu, "DOA Estimation for UCA in the Presence of Gain-Phase Errors".						
"Over a Century of Array Signal Processing", from the 2023 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	01 / 03 / 2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Li	To be released at the end of the 2022-2023 Lecturer Series
"Ultra Wide Band Surveillance Radar", from the 2023 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	21 / 03 / 2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Davis	To be released at the end of the 2022-2023 Lecturer Series
"Evolving Cyber Systems in Avionics", from the 2023 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	06 / 04 / 2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Kramer	To be released at the end of the 2022-2023 Lecturer Series
"Introduction to MIMO Radar Waveforms",	Seminar	1	0.2	13 / 04 / 2023	IEEE AESS	To be released at

from the 2023 Virtual Distinguished Lecturer Series.					(Aerospace and Electronic Systems Society), lecturer Sun	the end of the 2022-2023 Lecturer Series
"Design of Efficient Electrical Power Systems for Small Spacecraft", from the 2023 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	20 / 04 / 2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Gonzalez-Llorente	To be released at the end of the 2022-2023 Lecturer Series
WiFi and BlueTooth Low Energy: Architecture and Security	Seminar	30	6	9-10-16-17 / 03 /2023	CNIT - Consorzio Nazionale Interuniversitario Telecomunicazioni / University of Rome Tor Vergata, lecturer Gringoli	Y
Procedures and strategies for the evaluation of direction-finding performances of dual-polarization log-periodic circular antenna arrays. Production of internal report "Performance bounds for the DoA estimation with a log-periodic circular antenna array (with two possible polarizations)". Derivation of classical DoA estimators with arrays of directional	Research		4	Mar-Apr 2023		

elements and dual polarizations.						
Study of the following research papers: • "Data adaptive spectral analysis methods" (R. T. Lacoss); • "High-Resolution Frequency-Wavenumber Spectrum Analysis" (J. Capon); • "DOA Estimation for UCA in the Presence of Mutual Coupling via Error Model Equivalence" (W. Hu, Q. Wang); • "On the Performance Analysis of the MVDR Beamformer in the Presence of Correlated Interference" (M. D. Zoltowski)	Research		1	Mar-Apr 2023		
"Iron Stomachs and White Knuckles: Lessons Learned from 60 Years of Flight Testing", from the 2023 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	10 / 05 / 2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Braasch	To be released at the end of the 2022-2023 Lecturer Series
"Electromagnetics and Meter Wave Radar Scattering Theory", from the 2023 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	18 / 05 /2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Hellstein	To be released at the end of the 2022-2023 Lecturer Series
"Cognitive EW: Using AI to Solve EW Problems", from the 2023 Virtual	Seminar	1	0.2	31 / 05 / 2023	IEEE AESS (Aerospace and	To be released at the end of the 2022-2023

Distinguished Lecturer Series.					Electronic Systems Society), lecturer Haigh	Lecturer Series
"A Day in Space: Analog Astronaut Training", from the 2023 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	15 / 06 / 2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Ramirez	To be released at the end of the 2022-2023 Lecturer Series
"Advances in Digital Avionics and Space Systems", from the 2023 Virtual Distinguished Lecturer Series. *	Seminar	1	0.2	22 / 06 /2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Sabatini	To be released at the end of the 2022-2023 Lecturer Series
"Quantum Algorithms for Aerospace and Electronic Systems: Trends and Applications", from the 2023 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	28 / 06 / 2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Koch	To be released at the end of the 2022-2023 Lecturer Series
Lectures "SET-257 RLS Compressive Sensing Techniques for Radar and ESM Applications"	Seminar	16	1.6	15-16 / 05 / 2023	The NATO Science and Technology Organization, Lecturers Anitori, De Maio, Farina, Ertin, Martorella	Y
Initial work for the preparation of a research paper "Polarimetric Sparse Iterative Procedures for DOA Estimation", to be	Research		4	May-Jun 2023		

submitted to the 2023 IEEE International Workshop on Technologies for Defense and Security: • Definition of system model; • Design and adaptation of existing sparse procedures for the case of dual polarization; • Computer simulations and analysis; • Preparation and submission of the extended abstract.						
Study of the following research papers: • "Angle and polarization estimation using ESPRIT with a polarization sensitive array (J. Li, R. T. Compton); • "Compressed sensing based joint DOA and polarization angle estimation for sparse arrays with dual polarized antennas" (B. K. Chalise, Y. D. Zhang, B. Himed); • "SPICE: A sparse covariance-based estimation method for array processing" (P. Stoica, P. Babu, J. Li); • "Sparse methods for direction-of-arrival estimation" (Z. Yang, J. Li, P. Stoica, L. Xie).	Research		1	May-Jun 2023		
"Delay/Disruption-Tolerant Networking	Seminar	1	0.2	06 / 07 / 2023	IEEE AESS	To be released at

(DTN) for Deep Space Networks", from the 2023 Virtual Distinguished Lecturer Series.					(Aerospace and Electronic Systems Society), lecturer Wang	the end of the 2022-2023 Lecturer Series
"Design and Simulation of Nanosatellites", from the 2023 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	13 / 07 / 2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Ramon-Gonzalez	To be released at the end of the 2022-2023 Lecturer Series
"INFOrmation and Resource Management (INFORM) for Accurate Tracking of Resident Space Objects", from the 2023 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	26 / 07 / 2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Singla	To be released at the end of the 2022-2023 Lecturer Series
"3D ISAR: Techniques and Applications", from the 2023 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	01 / 08 / 2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Rosenberg	To be released at the end of the 2022-2023 Lecturer Series
"Integrated Sensing and Communications: A Dual-Blind Deconvolution Perspective", from the 2023 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	08 / 08 / 2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Vijay Misra	To be released at the end of the 2022-2023 Lecturer Series
"Foliage Penetration Radar", from the 2023 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	15 / 08 / 2023	IEEE AESS (Aerospace and	To be released at the end of the 2022-2023

					Electronic Systems Society), lecturer Davis	Lecturer Series
Completion and submission of the research paper "Polarimetric Sparse Iterative Procedures for DOA Estimation", submitted to the 2023 IEEE International Workshop on Technologies for Defense and Security: • Refinement of the system model; • Extension of computer simulations and analysis.	Research		5	Jul-Aug 2023		
Study of the following research papers: • "Multi-snapshot spectrum sensing for cognitive radar via block sparsity exploitation" (A. Aubry, V. Carotenuto, A. De Maio, M. A. Govoni); • "Weighted SPICE: A unifying approach for hyperparameter-free sparse estimation" (P. Stoica, D. Zachariah, J. Li); • "An Introduction To Compressive Sampling" (E. J. Candès, M. B. Wakin); • "Compressed Sensing" (D. L. Donoho).	Research		1			

PhD Summer School "Frontier Technologies for Space 2.0 Communications"	Doctoral School	24	5	29-30-31-01 / 08-09 / 2023	University of Trento and IEEE-AESS (Aerospace and Electronic Systems Society), Lecturers Sacchi, Ruggieri, Stallo, Cheung, Granelli, Guidotti, Bassoli, Notzel, Ferrara, Rossi, Codispoti, Popescu, Grayver, Marchese, Slim Alouini.	Y
"Advances in Detect and Avoid for Unmanned Aircraft Systems and Advanced Air Mobility", from the 2023 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	14 / 09 / 2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Fasano	To be released at the end of the 2022-2023 Lecturer Series
"Recent Research on Deep Learning Based Radar Automatic Target Recognition", from the 2023 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	21 / 09 / 2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Majumder	To be released at the end of the 2022-2023 Lecturer Series
"An Introduction to Quantum Computing and Data Fusion", from the 2023 Virtual	Seminar	1	0.2	28 / 09 /2023	IEEE AESS (Aerospace and	To be released at the end of the 2022-2023

Distinguished Lecturer Series.					Electronic Systems Society), lecturer Govaers	Lecturer Series
"Measurement Extraction for a Point Target From an Optical Sensor", from the 2023 Virtual Distinguished Lecturer Series.	Seminar	1	0.2	10 / 10 /2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Bar-Shalom	To be released at the end of the 2022-2023 Lecturer Series
"Multiple-Hypothesis Tracking", from the 2023 Virtual Distinguished Lecturer Series. **	Seminar	1	0.2 **	26 / 10 /2023	IEEE AESS (Aerospace and Electronic Systems Society), lecturer Coraluppi	To be released at the end of the 2022-2023 Lecturer Series
Review of the research paper "Polarimetric Sparse Iterative Procedures for DOA Estimation", submitted to the 2023 IEEE International Workshop on Technologies for Defense and Security, based on feedbacks and requests from IEEE reviewers.	Research		2	Sep-Oct 2023		
Study of the following research papers: "Signal recovery from partial information via orthogonal matching pursuit" (J. Tropp, A.C. Gilbert); "Robust uncertainty principles: Exact signal reconstruction from highly incomplete frequency information,"	Research		2	Sep-Oct 2023		

(E. Candès, J. Romberg, T. Tao).						

1) Courses, Seminar, Doctoral School, Research, Tutorship
2) Choose: Y or N

NOTES

* Seminar attended within the 2023 Virtual Distinguished Lecturer Series. By mistake, not included within the periodic BSR Report. The relevant credits (0.2) are not included in the total in the following paragraph.

** Seminar included within the 2023 Virtual Distinguished Lecturer Series, scheduled before the end of the 2nd PhD year but not yet attended at the time of this TRAT Report. The relevant credits (0.2) are not included in the total in the following paragraph.

2.1. Study and training activities - credits earned

	Courses	Seminars	Research	Tutorship	Total
Bimonth 1		3	5	0	8
Bimonth 2	3	2	7	0	12
Bimonth 3		7	5	0	12
Bimonth 4		2.6	5	0	7.6
Bimonth 5		1.2	6	0	7.2
Bimonth 6	5	1	3	0	9
Total	8	16.8	31	0	55.8
Expected	30 - 70	10 - 30	80 - 140	0 – 4.8	

3. Research activity:

MAIN TOPIC - **Novel algorithms for the Direction-of-Arrival (DoA) estimation in radar and communication problems**

The general research topic for this PhD program is represented by the **estimation of the Direction-of-Arrival (DoA) of radio waves**, in non-cooperative environments and when no or little information is available at a radio receiver about the incoming signals. The theoretical framework and the tools of **array processing** help coping with such a task, through the observation of the signal samples available at each antenna element. The estimate of the DOA can be important on its own (for instance in situations where the goal is to localize an emitter) or can in general help optimizing reception in communication systems and detection and tracking performances in radars.
In greater detail, we are especially interested in developing new algorithms or refining existing ones that could achieve satisfactory performances in the presence of multiple dimensions and unknowns (azimuth, elevation, frequency, range, polarization, etc.), while maintaining a reduced computational complexity, suitable for the implementation with current commercial-grade SDR (Software-Defined-Radio) architectures. Although such techniques could be employed in several scenarios, they could be initially

preferably tested and specifically adapted for some radio and radar applications of specific interest (e.g. direction finding in the HF spectrum).
With such a goal and stemming from the studies performed and the research directions identified during the first PhD year, the research activity during the second year has been carried out with respect to the sub-topics and areas reported below.

TOPIC – **Classical DoA estimators in circular arrays**

Uniform Circular arrays (UCA) play a special role in DOA estimation and for the applications of interest especially. They have long been used throughout history, are widespread all over the world and their symmetrical structure often allows a simpler mathematical description.
Starting from the works of Zoltowski and Mathews, it was shown that the ESPRIT (*Estimation of Signal Parameters via Rotational Invariance Techniques*) method can be conveniently modified (yielding to the so-called UCA-ESPRIT technique) in order to work with circular arrays too.
UCA-ESPRIT emerges as a powerful technique for simultaneous azimuth and elevation estimation, because it automatically provides the estimate pair (azimuth, elevation) in closed form from the eigenvalues of a a matrix associated with the array and does not require the extensive 2D grid searches that other classical methods need (such as MUSIC – *Multiple Signal Classification*). The sine of the elevation, in detail, depends on the absolute value of the eigenvalue. However, in the presence of noise and for low SNR values especially, the eigenvalues can be larger than unity in absolute value, bringing to meaningless elevation estimates.

METHODOLOGY
A modified version of UCA-ESPRIT was devised in order to deal with the above cited situation. Whenever the eigenvalues of interest are equal or smaller than one in absolute value, the UCA-ESPRIT direct estimates of azimuth and elevation are maintained. A different approach is taken on the other hand in the opposite case: the azimuth estimate, which only depends on the phase of the eigenvalue, is maintained, while the elevation estimate is discarded and a new suitable elevation is computed through MUSIC for instance (with a 1D search, since the azimuth is assumed known).
This algorithm was finally tested through computer simulations, for varying SNR conditions and arrays' parameters (number of elements, radius over wavelength, etc).

RESULTS
The simulations show that the newly devised algorithm gets rid of the meaningless elevation estimates which the standard UCA-ESPRIT may produce in case of large eigenvalues. In this respect, it achieves a lower RMSE of the estimates for low SNR values. At the same time the computational complexity is comparable to the standard UCA-ESPRIT and only in a few occurrences (the ones where UCA-ESPRIT fails) requires an additional 1D grid search.
The modified UCA-ESPRIT thus appears as a suitable solution for 2D (azimuth, elevation) DOA estimation in circular arrays under general circumstances.

TOPIC – **Antenna coupling conditions**

Mutual coupling between the antenna elements is a typical situation in array antennas but can have a significant impact and degrade the resolution capability, robustness to the interference, and accuracy of

DOA estimation. In some applications of interest (in the HF spectrum), additionally, antenna coupling can be even more important, due to large wavelengths and the need to constrain the array size.
Offline and online calibration methods have been developed over time: the former use first a known incoming signal in order to estimate the coupling terms and subsequently compensate for them while estimating the DOAs of unknown signals; online methods on the other hand attempt to jointly estimate the DOAs and the antenna coupling terms from unknown incoming signals.
Armed with the initial research reported in the previous sub-area, we aimed at developing an iterative online method, suited for uniform circular arrays and the UCA-ESPRIT technique.

METHODOLOGY
In uniform circular arrays it is licit to assume the mutual coupling matrix (MCM) collecting all the coupling terms between any two array elements as a complex circulant Toeplitz matrix.
The same beamspace transformation used for deriving UCA-ESPRIT (based on phase-mode excitation) was considered. This transformation allows to describe the UCA array manifold matrix in terms of a beamspace manifold with the typical structure of a ULA (Uniform Linear Array).
The combination of this transformation with a circulant coupling matrix was investigated and shown to produce a VULA (Virtual ULA) manifold, affected with phase and gain errors.
At this stage, ML (Maximum Likelihood) estimates of the unknown DOAs, the signal amplitudes, and the gain and phase error terms can be searched by solving a least-square problem, that is to say minimizing the sum over the observed snapshots of the squared errors between the transformed received samples and the (phase and gain errored) transformed impinging signals.
The resulting function has several unknowns and is not convex. We therefore opted for designing an approximate iterative optimization method, based on an alternating optimization procedure over different blocks of variables. In detail, the method proposed alternately:

- optimizes over the phase and gain error terms and the signal amplitudes, assuming the DOAs fixed. This is achieved through a CD (Coordinate Descent) method;
- then leverages the estimate phase and gain error terms and the signal amplitudes in order to obtain an updated and refined estimate of the DOAs via the application of the UCA-ESPRIT method on the calibrated VULA.

Suitable initialization values for the unknown terms and stop criteria were proposed too.
The behaviour of the algorithm was tested through extensive simulations, taking into account changing SNR ranges, and number and correlation of radio sources.

RESULTS
The proposed iterative calibration method proved to be a fast-converging technique able to provide monotonic decreasing objective function values. The simulation results have demonstrated the capabilities of the proposed method to yield accurate DOA estimates in the presence of mutual coupling.
Additionally, in the mathematical description of the optimization problem it was possible to obtain closed form expressions for the updates of the estimates of the error terms and the signal amplitudes.

TOPIC – **Characterization of Dual-polarimetric arrays**

Arrays made up of two similar sub-arrays with orthogonal polarizations have attracted special attention recently and have been implemented in some commercial solutions. In general, the availability of two structures with orthogonal polarizations makes such a receiving asset inherently robust with respect to unknown or changing polarization of the incoming radio waves. Polarization is thus an additional (unknown) parameter that can be potentially estimated and exploited.
In practice, hovewer, often only sub-optimal DOA estimation methods are adopted with dul-pol arrays.
The purpose of the research in this sub-topic was thus to initially develop a mathematical characterization of these dual-polarimetric arrays, which could be later used to derive appropriate DOA estimation methods.

METHODOLOGY
A combined array manifold was defined, in which the steering vectors of the two sub-arrays appear. The signal vector at each snapshot can be obtained as the product of this array manifold with the array of the complex amplitudes of the two polarizations.
With the help of the Slepian-Bangs formulas, an expression for the Cramer Rao Bound (CRB) for the estimates of the azimuth and the elevation was obtained, for the cases of known or unknown complex amplitudes.
Similarly, it was possible to derive compact expressions for the ML estimators and the Capon / MVDR (*Minimum Variance Distortionless Response*) estimators.
After laying down these mathematical foundations, a particular use case was considered, with a circular array made up of two sub-arrays of log-periodic elements, respectively with horizontal and vertical polarizations. This structure was specifically designed within the scope of another project and the data of the steering vectors for different HF frequencies and incoming directions were available.
For this specific array, the CRB was computed and compared with the RMSE for the DOA estimates given by the other estimators (dual-pol ML, dual-pol Capon, etc.).

RESULTS
The simulations show that the proposed polarimetric methods achieve the CRB performances limits for growing SNRs. It was worth noting that with equal received overall power, the best performances achieved exploiting both the two subarrays substantially coincide with the best performances obtainable for a single polarimetric array. By the way, the methods optimized for the dual polarimetric array will have the benefit to keep on performing when one of the polarization components goes down significantly.

TOPIC – **Sparse Iterative procedure and Dual-polarimetric arrays**

Compressed sensing techniques assume a sparse representation of a physical problem (that is to say with only few elements different from zero when represented in an appropriate basis) to achieve the reconstruction of a signal from limited and noisy observations.
With reference to this topic, the extension of some iterative spare algorithms for DOA estimation was investigated for polarimetric sensor arrays equipped with receive pairs of orthogonal / crossed dipoles. For sake of simplicity, elevation was initially ignored and only the azimuth estimated.

METHODOLOGY
A sparse signal model was proposed for the problem, where the atoms are represented by the steering vectors of the two sub arrays for each point of an azimuth search grid, with a similar approach and notation as the ones built in the previous research sub-topic.
Based on this signal model, two well-established iterative and hyperparameter-free strategies, leveraging the signal sparsity, were selected as candidates for Doa estimation, namely SLIM (*Sparse Learning via Iterative Minimization*) and SPICE (*Sparse iterative covariance-based Estimation*).
Two new methods were derived from them and tailored to the polarimetric case of interest, named POL-SLIM and POL-SPICE.
POL-SLIM attempts to solve the problem of estimating the sparse parameters by directly recovering the unknown signal matrix. The optimization problem for the objective function (which depends on the signal matrix, the interference variance and some penalty terms promoting sparsity) was addressed through an iterative procedure, wherein at each step the variables representing the signal matrix and the unknown interference variance are individually optimized by keeping the others fixed.
POL-SPICE, instead, estimates the signal covariance matrix by resorting to a Coordinate Descent optimization of a minimization problem over different group of variables.

RESULTS
The two new polarimetric methods were tested through computer simulations with a circular array made up of two circular subarrays with horizontal and vertical dipoles.
Extensive numerical analysis shows the effectiveness of POL-SLIM and POL-SPICE in accurately estimating the sources DOA, with both small and large number of collected snapshots, attaining the Cramér-Rao bound (CRB) at a lower signal-to-noise ratio value than the single polarization counterparts.

4. Research products:

- Conference papers:
  - M. Boddi, M. Rosamilia, A. Aubry, and A. De Maio, "Iterative Direction-of-Arrival Estimation for a Uniform Circular Array in the Presence of Mutual Coupling," SET-319/RSM Specialist Meeting “New Mathematics for Multi-Dimensional Radar Systems”, published, 2023, presented in Edinburgh, 21-23 February 2023.
  - M. Rosamilia, M. Boddi, A. Aubry, and A. De Maio, " Polarimetric Sparse Iterative Procedures for DOA Estimation," 2023 IEEE International Workshop on Technology for Defense and Security, accepted, 2023, to be presented in Rome, 20-22 November 2023.

The paper “Iterative Direction-of-Arrival Estimation for a Uniform Circular Array in the Presence of Mutual Coupling” was awarded as “Best Paper – Young scientist” at the NATO SET-319/RSM Specialist Meeting.

5. Conferences and seminars attended

- 2022 Radar Virtual Distinguished Lecturers Series, attended on line, arranged by IEEE (Institute of Electrical and Electronics Engineers) AESS (Aerospace and Electronic Systems Society), with the following seminars:
  - "Simulation of Radar Sea Clutter", lecturer Prof. L. Rosenberg, 14/11/2022;
  - "Gravity-Modeling Considerations in High-Integrity Inertial Systems", lecturer Prof. M. Braasch, 30/11/2022;
  - "Radar Technology and Sustainability: How to Conjugate Innovation and Social Duties", lecturer Prof. A. Farina, 05/12/2022;
  - "Cognitive Radars", lecturer Prof. S. Greco, 14/12/2022;
- 2022 Radar Virtual Distinguished Lecturers Series, attended on line, arranged by IEEE (Institute of Electrical and Electronics Engineers) AESS (Aerospace and Electronic Systems Society), with the following seminars:
  - "Over a Century of Array Signal Processing", lecturer Prof. J. Li, 01/03/2023;
  - "Ultra Wide Band Surveillance Radar", lecturer Dr. M. E. Davis, 21/03/2023;
  - "Evolving Cyber Systems in Avionics", lecturer Prof. K. Kramer, 06/04/2023;
  - "Introduction to MIMO Radar Waveforms", lecturer Dr. H. Sun, 13/04/2023;
  - "Design of Efficient Electrical Power Systems for Small Spacecraft", lecturer J. Gonzalez-Llorente, 20/04/2023;
  - "Iron Stomachs and White Knuckles: Lessons Learned from 60 Years of Flight Testing", lecturer Prof. M. Braasch, 10/05/2023;
  - "Electromagnetics and Meter Wave Radar Scattering Theory", lecturer Prof. H. O. Hellstein, 18/05/2023;
  - "Cognitive EW: Using AI to Solve EW Problems", lecturer Dr. K. Haigh, 31/05/2023;
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  - "Advances in Digital Avionics and Space Systems", lecturer Prof. R. Sabatini, 22/06/2023;
  - "Quantum Algorithms for Aerospace and Electronic Systems: Trends and Applications", lecturer Prof. W. Koch, 28/06/2023;
  - "Delay/Disruption-Tolerant Networking (DTN) for Deep Space Networks", Prof. R. Wang, 06/07/2023;
  - "Design and Simulation of Nanosatellites", lecturer Prof. A. Roman-Gonzalez, 13/07/2023;
  - "INFOrmation and Resource Management (INFORM) for Accurate Tracking of Resident Space Objects", lecturer Prof. P. Singla, 26/07/2023;
  - "3D ISAR: Techniques and Applications", lecturer Prof. L. Rosenberg, 01/08/2023;
  - "Integrated Sensing and Communications: A Dual-Blind Deconvolution Perspective", lecturer Dr. K Vijay Mishra, 08/08/2023;
  - "Foliage Penetration Radar", lecturer Dr. M. E. Davis, 15/08/2023;
  - "Advances in Detect and Avoid for Unmanned Aircraft Systems and Advanced Air Mobility", lecturer Prof. G. Fasano, 14/09/2023;
  - "Recent Research on Deep Learning Based Radar Automatic Target Recognition", lecturer U. K. Majumder, 21/09/2023;

- "An Introduction to Quantum Computing and Data Fusion", lecturer Dr. F. Govaers, 28/09/2023;
- "Measurement Extraction for a Point Target From an Optical Sensor", lecturer Prof. Y. Bar-Shalom, 10/10/2023;

- NATO SET-319/RSM Specialist Meeting "New Mathematics for Multi-Dimensional Radar Systems", Edinburgh, 21-23 February 2023, arranged by NATO Science and Technology Oragnization (S&T) and the Isaac Newton Institute Research Programme;
  - Paper presented "Iterative Direction-of-Arrival Estimation for a Uniform Circular Array in the Presence of Mutual Coupling", M. Boddi, M. Rosamilia, A. Aubry, A. De Maio;
- NATO SET-257 RLS Lecture Series "Compressive Sensing Techniques for Radar and ESM Applications", Rome, 15-16 May 2023, organized by the NATO Systems and Electronics Technology (SET) Panel.

6. Periods abroad and/or in international research institutions

None, apart for the participation into conferences and workshops abroad (see para. 5).

7. Tutorship

None.

8. Plan for year three

- Research activities:
  - Investigate the extension of the sparse polarimetric DOA methods to 2D DOA estimation (elevation, azimuth);
  - Investigate the extension of the sparse polarimetric DOA methods to arrays made up of subarrays with elements with different steering vectors (additional structures, not only arrays of crossed dipoles);
  - extend the theoretical framework of subspace fitting models and sparse matrix methodologies to jointly deal with additional multiple dimensions of interest (range, azimuth, elevation, frequency, polarization, etc.);
  - adapt the theoretical models to real-world radar and communication environments, and assess the feasibility and understand limits of a sparse representation of these scenarios;
  - implement algorithms on SDR platforms and test through on-field measurements.
- Draft topic or title of the thesis:
  - Novel algorithms for the Direction-of-Arrival (DoA) estimation in radar and communication problems.