

***Exploring the Architecture of Combat Air Operations:
Insights into Flexibility in Enterprise Architectures and
Implications for System Architecture and Acquisition***

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Observations

Technical, organizational complexity

increasing

Enterprise change/transformation

ineffective

Concepts that work

hard to find

Interactions and interdependencies

underappreciated

Designing enterprises and systems

black art

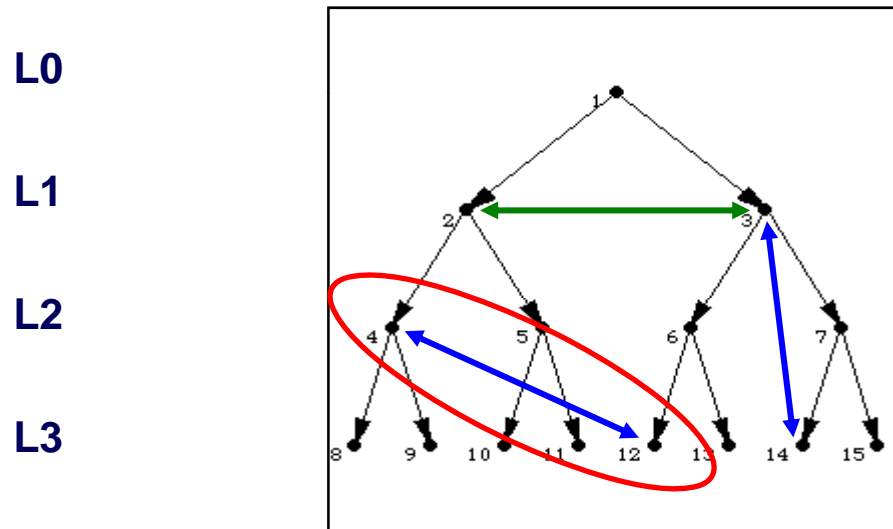


- **Question:**
 - How do we design enterprises and large-scale systems for flexibility?
- **Hypothesis:**
 - Enterprise and technical system architectures with more lateral vs. vertical connections will perform better in dynamic and uncertain environments, both operational and acquisition
- **Goals:**
 - Architectural analysis at enterprise level to see whether a shift from an architecture dominated by vertical connections to one dominated by lateral connections enables an enterprise to achieve greater flexibility.
 - Associate this shift to performance
 - “First Order” modeling and analysis

Motivating Case: Combat Air Operations

- **Kometer: “Command in Air War”, MIT Ph.D. thesis, 2005**
 - Relevance of AF doctrinal tenet in information age context
- **CLIOS Analysis**
 - Sense-Decide-Act-Assess chain increasingly fragmented
 - Benefits: time responsiveness, flexibility
 - Dark side: System accidents--lack or loss of control
- **Prescriptions:**
 - General formula for command and control
 - Depth of Command
- **Issues:**
 - Full potential benefits of information age unrealized
 - No way to gauge “depth” precisely or to assess relative merits among architectural choices

- **Classic hierarchy as the foundation**
 - Two basic modifications to create all varieties of structures
 - vertical connections (across branch boundaries and across layers)
 - lateral connections (within layers)



Classification*

- Parents
- Grandparents
- Cousins
- Uncles

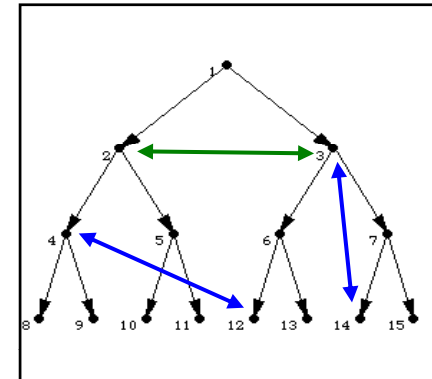
- **Enterprise as a resource and information processing system**
 - Information or physical resource flow paths (including loops--once)
 - Task or function chain combinations



* this nomenclature is due to Joel Moses

Operationalizing connections

- **Lateral ratio:** Collaboration-enabler of flexibility
- **Vertical violations: Complexity**
 - potential for confusion, conflicting directives
- **# Paths; # Function chains: Flexibility**
- **In(paths/node): Efficiency (of marginal link)**
- **In(paths): Flexibility**
- **Laterality: # lateral connections/ # total connections**



Structure	Nodes	# added connections	Laterality	In(# Paths)	In(paths/node) (efficiency)
Tree	15	0	0	2.1	-.63
Vertical only	15	14	0 (.16)*	3.5	0.79
Lateral only	15	14	0.5	5.6	2.84

Hypothesis: Enterprises and technical system architectures with more lateral vs. vertical connections will perform better in complex, dynamic and uncertain environments, both operational and acquisition

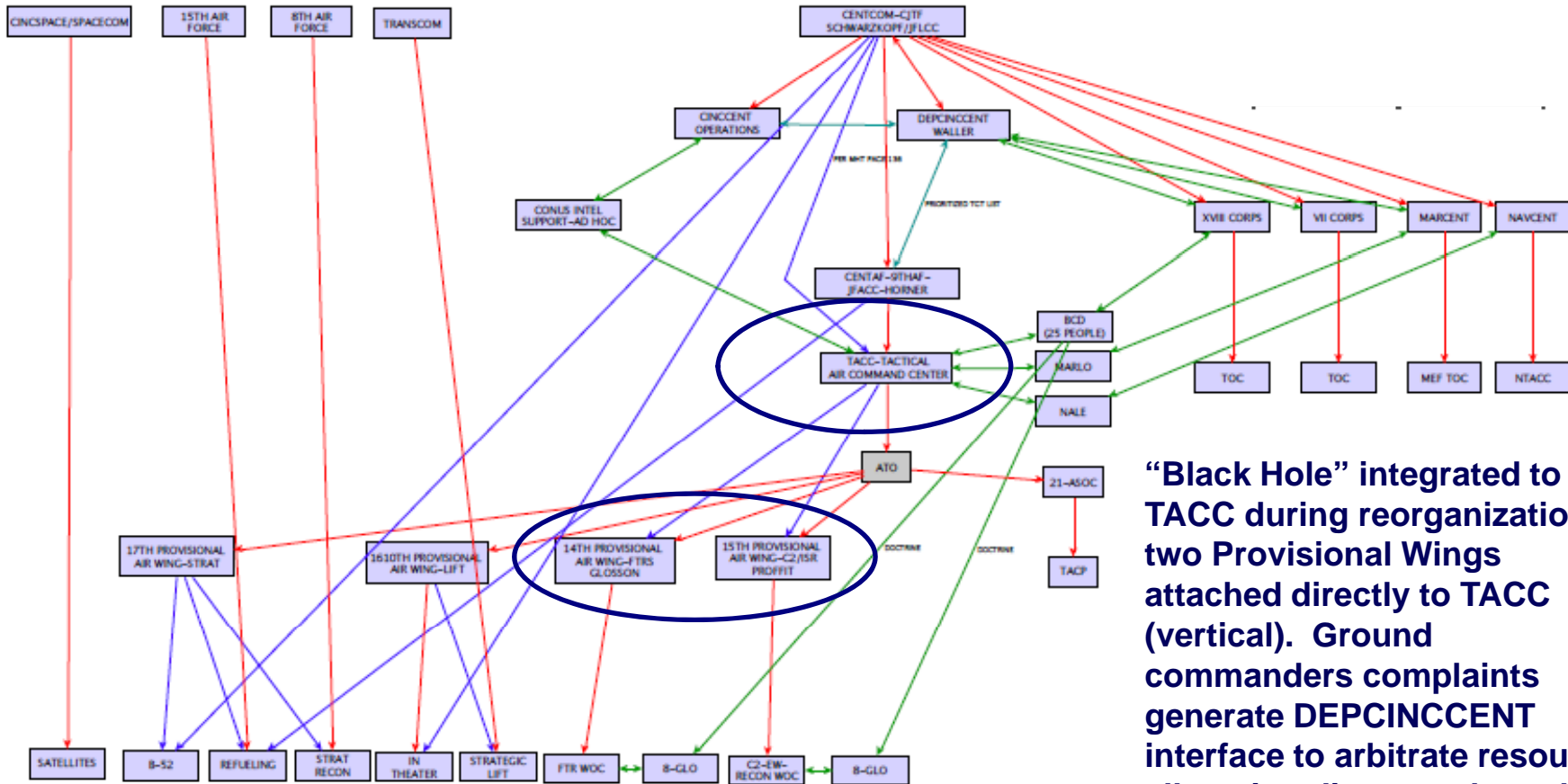


* “uncle” connections count .5 lateral, .5 vertical

Characterizations of Air Power C2 through 1990s

- **Desert Storm:**
 - Individual service plans, integrated at the top
 - Ref: GWAPS, Mandeles, et al., Kometer
- **Kosovo (Allied Force)**
 - Tightly controlled, highly constrained, driven from the top
 - Ref: Haun, Haave and Haun, Cordesman, Lambeth, Kometer
- **Afghanistan (Enduring Freedom)**
 - Tight control for certain targets, loose for others; low information and sortie load (air operations)
 - Failed (almost) when operational conditions changed
 - Ref: Kometer, USAF Lessons Learned
- **Iraq-II (Iraqi Freedom to end of MCO)**
 - Integrated service plans, Joint, coordinated
 - Ref: Murray and Scales, Kometer, Gordon and Trainor, Service Lessons Learned

Air Operations C2* 1991: Desert Storm-II



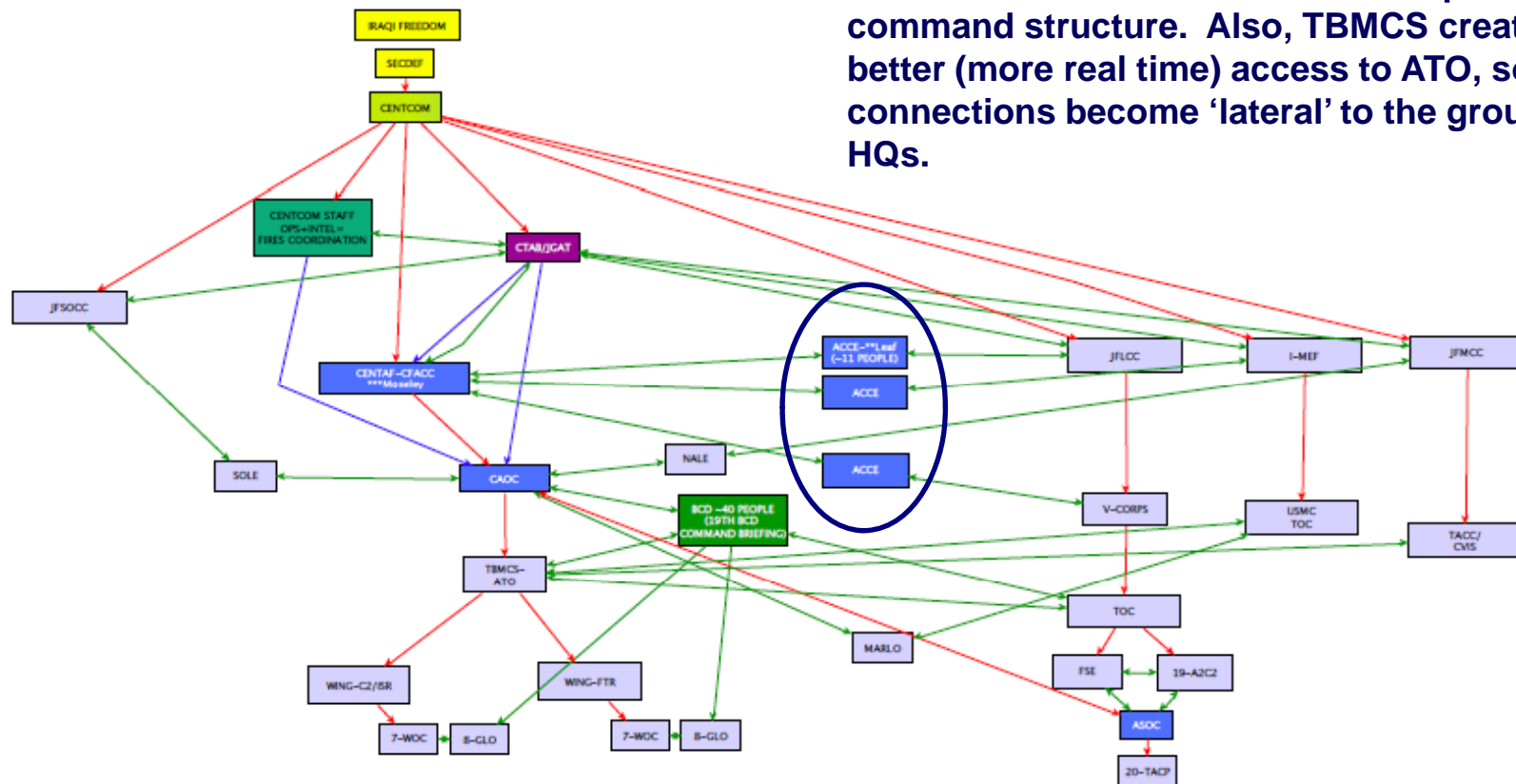
“Black Hole” integrated to TACC during reorganization; two Provisional Wings attached directly to TACC (vertical). Ground commanders complaints generate DEPCINCENT interface to arbitrate resource allocation disputes--lateral connection; possibly a new organizational layer.



*Preliminary diagrams

Air Operations C2* 2003: Iraqi Freedom

ACCE added to the architecture specifically to ensure lateral connections at the top of the command structure. Also, TBMCS creates better (more real time) access to ATO, so these connections become 'lateral' to the ground HQs.



*Preliminary diagrams



Technical Architecture Evolution

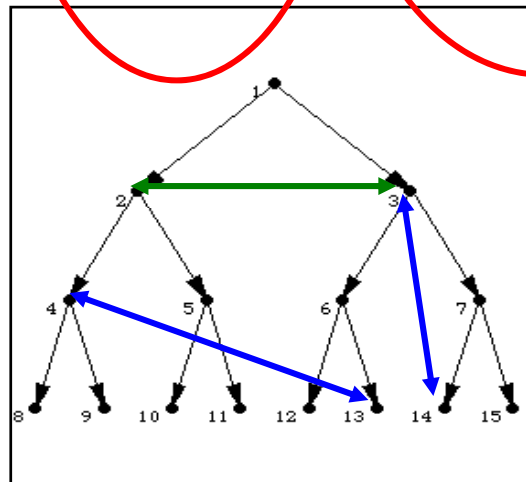
(Selected trends in system acquisition)

- **Kosovo:**
 - Predator video piped to AOC, SHAPE, Beale, JAC
 - Predator laser used to illuminate F-15 LGB (tested, never used)
 - Sure Strike: one way Ground → F-16, xyz coordinates
- **Afghanistan:**
 - Predator video linked to AC-130
 - SOF lasers and GPS to support CAS
- **OIF**
 - BUG-E gateway to connect SADL F-16s to Link-16 network
- **All are examples of increasing laterality--focused on the tactical level of system and organization**

Initial Results

(Enterprise Level)

Structure	Nodes	Edges	L/V	Turbulence	# Paths		In(paths/node) (efficiency)	
					One way	Loops		
DS-I	32	41	.32	.2	8	23	-1.4	-.33
DS-II	38	51	.42	.2	194	71000	1.6	7.5
KOSOVO	18	32	.19	.4	55	386	1.1	3.1
AFGHANISTAN	23	47	.81	.15	3167	52.3B	4.9	21.5
IRAQ-II	32	52	1.1	.06	2254	313.2B	4.3	23



Potential Insights

- **Laterality is an architecturally observable feature at the enterprise level**
 - **Initial indicators as a metric track with qualitative analysis**
 - **Upper limit to benefits of laterality not explored**
 - **Informal laterality precedes formal institutionalization**
- **Qualitatively:**
 - **Trend toward laterality/interoperability in technical systems**
 - **Tactical level laterality balanced by**
 - **Tactical-Operational level verticality**
 - **Acquisition system strongly influences operational capabilities enabled by interoperability**
 - **Western theater in OIF (Link-16; BUG-E; SADL)***
 - **High level acquisition design rules may inhibit technical architecture change, and, hence, enterprise flexibility:**
 - **Western OIF comment re: Predator + Link 16***

*MITRE-OFT interview data from NCO case study



Practical Relevance

- **We aim to**
 - quantify flexibility in technical and organizational architectures
 - yield insight to the marginal value of an added interaction/interface
- **In program management contexts, taking a lateral view toward architectures may highlight interactions that**
 - help mitigate cost-schedule-risk-performance issues (A-RCI case study)
 - help better understand efficiency-effectiveness trade-offs in large scale technical and organizational designs
 - relax technical constraints and enable flexibility and agility in response to operator demands

- **Systems that enable flexibility in operational forces have more value**
 - Predator-to-AC-130
 - SADL/BUG-E/Link-16
- **Laterality may enable balanced efficiency-effectiveness trades**
- **Architectural analysis can provide insight that improves enterprise and system design and management**

Backups

Architecture

- “... the scheme by which the functional elements of the product are arranged in to physical chunks and by which the chunks interact”--Ulrich and Eppinger, 1995
- “The embodiment of concept, and the allocation of physical/informational function to elements of form, and definition of interfaces among the elements and with the surrounding context”--Crawley, 2004
- “the grouping boundaries and linking processes, the patterns of personal and cultural relationships that get work done in certain ways, the interaction of the social and the technical asides of the organization.”--Nadler and Tushman, 1997

Work to be Done

- **Connect technical system architectures more closely to enterprise architectures**
- **Analyze more closely laterality in a system-of-systems context**
- **Explore more deeply the long vs. short time scale architectural changes**
- **Synthesize across cases (finish data gathering): ARCI**
- **Understanding better the efficiency-effectiveness/control-autonomy trade-off**

- **Data access and fidelity**
 - Balance between overwhelming volume (too much detail) and not enough (too abstract)
 - Operations Research vs. History
- **Adequately capturing technical architectures**
 - Static vs. dynamic views
 - Types of interactions: information, control, range
- **Air Operations:**
 - “We have no way to know how these systems actually get used; they are not instrumented”--MITRE engineer supporting AOC acquisition
- **“So what--we already know that lateral communication happens”**
 - Sosa (product development), Mandeles (GWAPS)

Descriptions of Enterprise Design Practice

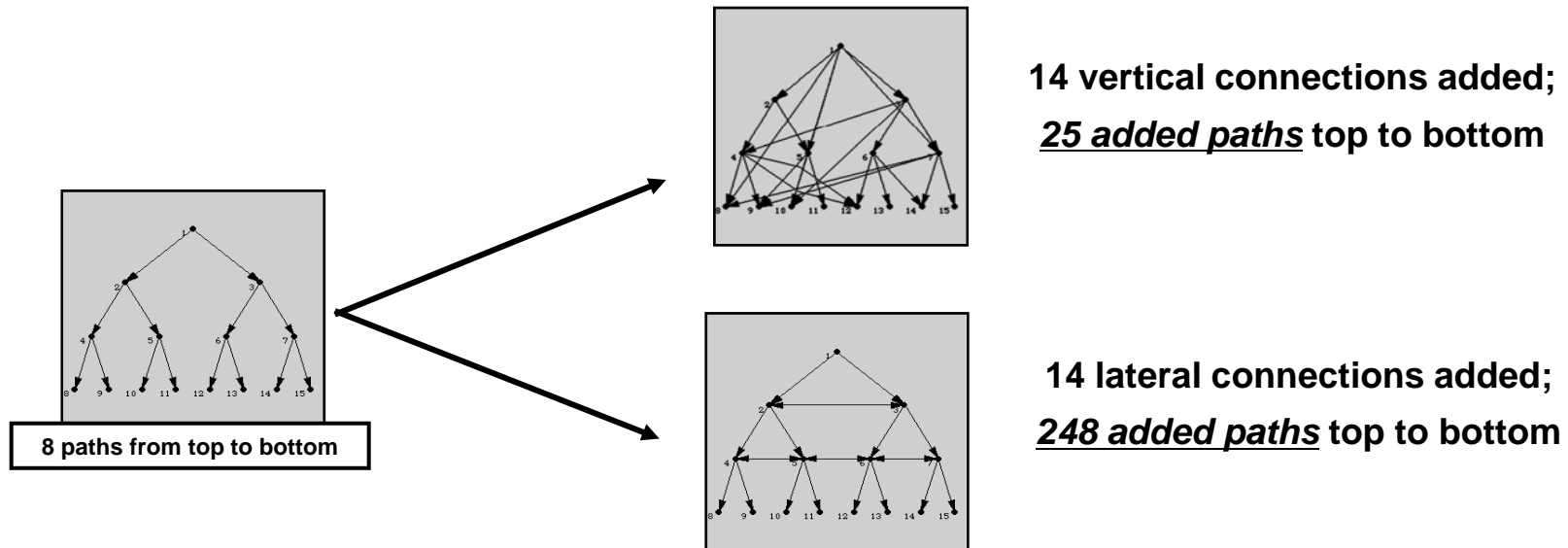
- **“Just get good people and let them work”; “...it was just a natural evolution...”**
 - LGEN Horner on Operation Desert Storm TACC design
- **“The job couldn’t have been done without the informal information channels between CONUS and the theater”**
 - SecAf Rice on back channel communications during Operation DS
- **“... an army SF Group was reorganized to operate as the CFSOCC and later as a JSOTF”**
 - Major Mark G. Davis, USA, Air University Thesis, 2004
- **“We created a system where data and professional reputation mattered more than defending an organizational position.”**
 - Deputy Program Manager, Navy acquisition program

Can we do better?



The Basic Idea

- **Paths through the architecture from top to bottom are a measure of flexibility**



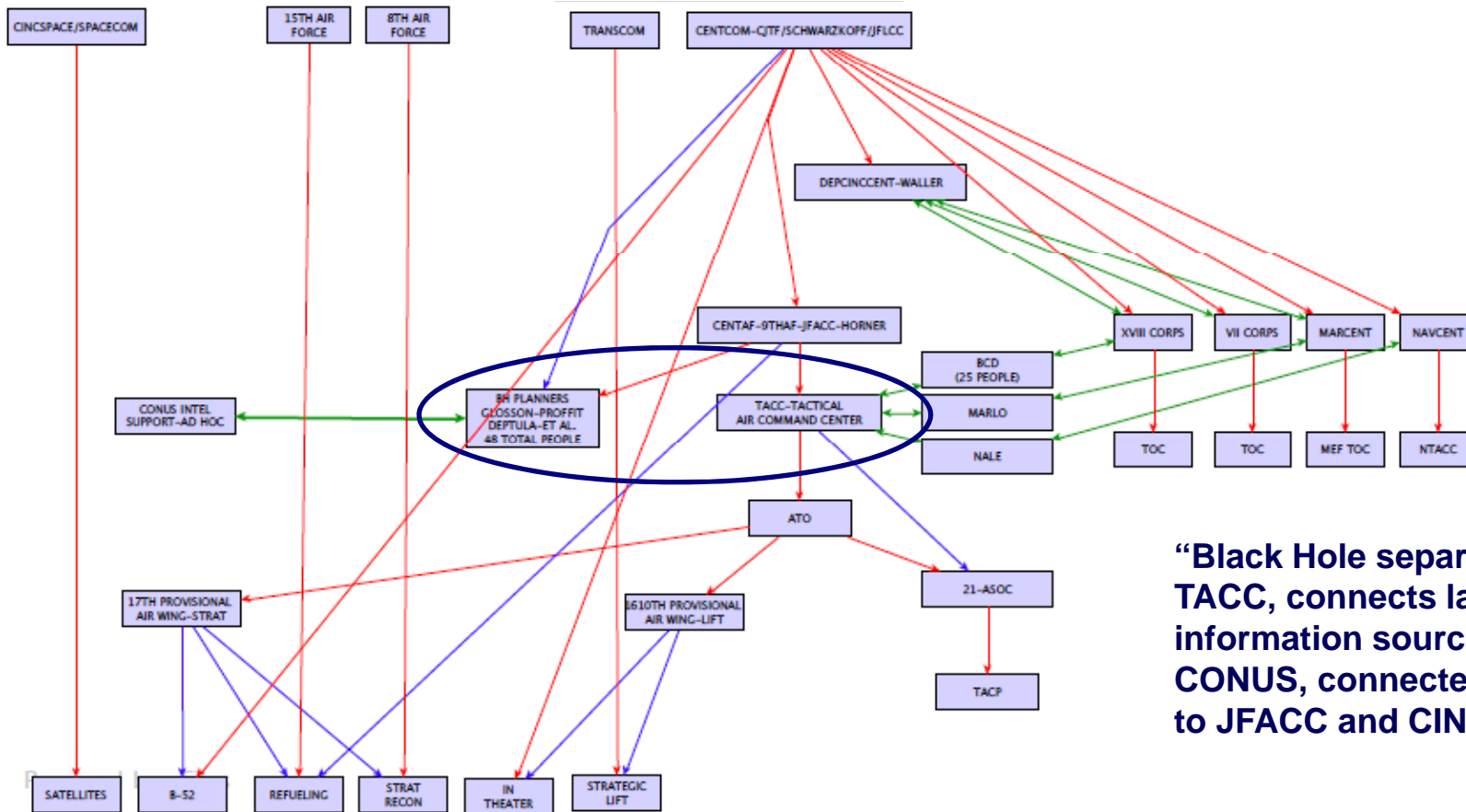
- **Kometer Ph.D. thesis: “Command in Air War” (2005)**
 - Examined AF command and control doctrinal tenet: “Centralized control, decentralized execution” in the information age
 - Four air campaigns, 1991-2003
- **Analysis:**
 - Information, decision, action, assessment loop became
 - Distributed (across many different battle and non-battle organizations)
 - Dispersed (globally)
 - Information processing concentrated at HQs
 - Ability to violate hierarchical boundaries easier
 - Two key determinants of enterprise architecture
 - External constraints (politics and strategy)
 - Locus of information processing and fusion (risk management)
 - Consequences unclear
 - System accidents
 - Precision-empowerment tradeoff (control-flexibility)

Can we move toward a model?

*CLIOS: Complex Large-scale Integrated Open System



Air Operations C2* 1990: Desert Shield

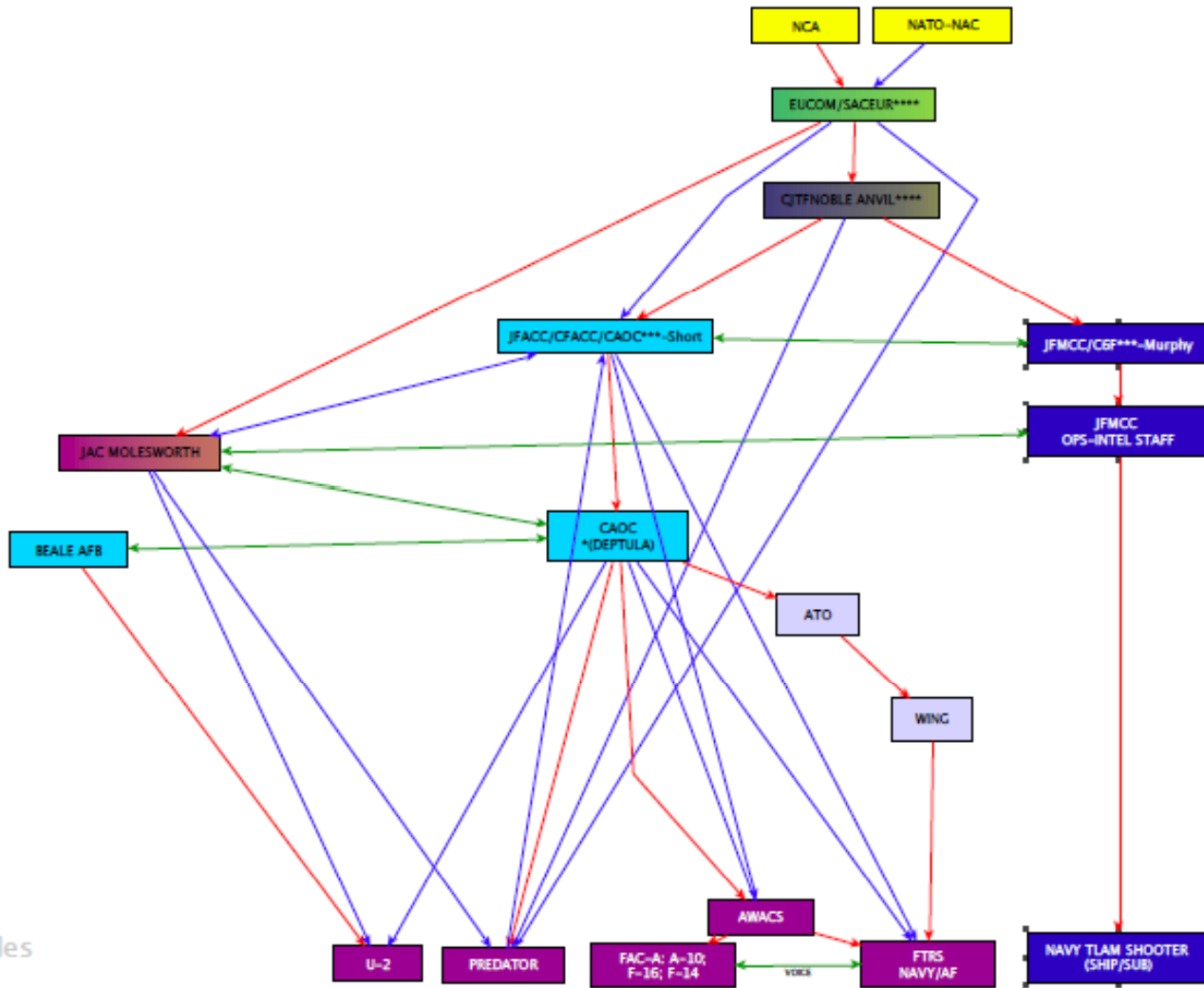


“Black Hole separate from TACC, connects laterally to information sources in CONUS, connected vertically to JFACC and CINCCENT

*Preliminary diagrams



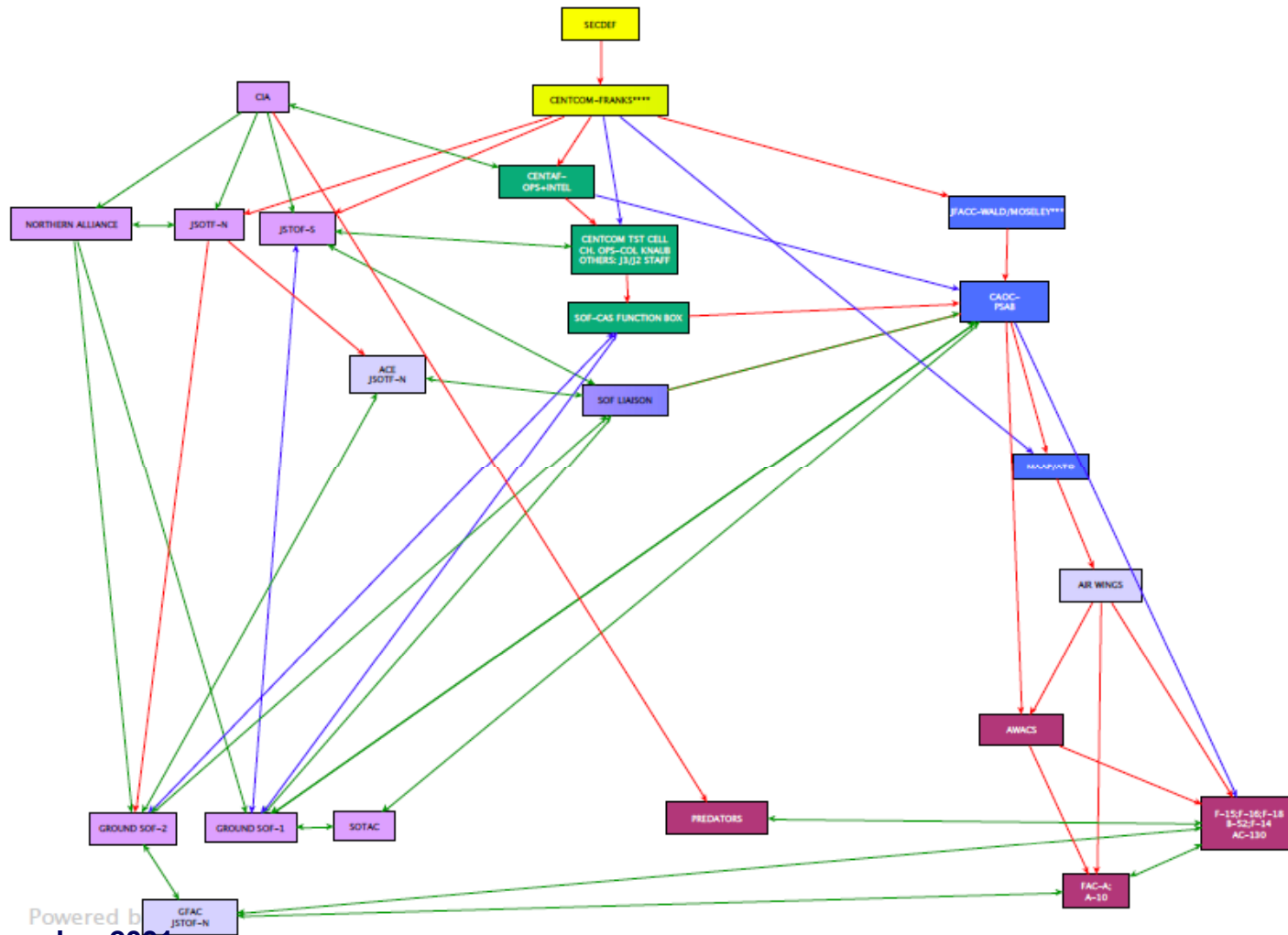
Air Operations C2* 1999: Kosovo



*Preliminary di files



Air Operations C2 2001-2002: Afghanistan*



Powered by
*Pre-December 2001



Ways to approach study (architectural/network perspective)

- Describe architectures
- Understand how architecture enables/inhibits behavior
 - Generally short time scales (static)
 - Performance variables vs. structure
- Architectural evolution vs. time
 - Behavior changes structure
 - Externalities change structure



Key: Finding the right level of abstraction that adds precision without losing generality

- **Data**
 - Fidelity
 - Access
- **Analytical tractability at appropriate scale**
 - Many dimensions to interactions,
 - Many dimensions to classification of nodes in a hierarchical framework
- **Generalizability--specifically, second and third case studies to show applicability to the following:**
 - Defense acquisition
 - Commercial

- Architectures at this point are at the ‘enterprise’ level: major reported interactions (formal and informal) between and among operational level organizations and operational forces, down to a contextually consistent level of abstraction
 - No guarantees that reported interactions are either representative or comprehensive
- Next steps are to look at specific architectures relevant to air operations: Time Critical/Sensitive Targeting
 - Detailed look at process, organizational and technical architectures over the time period of interest, to include, if possible, JEFX architectures as well
 - Possible that data is more consistent and reliable
- Building a model similar to D-W-S will require leveraging these architectures and estimating stochastic variables that generate linkages/connections.*

*Ref: Dodds, et al, PNAS, 1999 “information exchange and the robustness of organizational networks

Two Areas of Interest

- **What architectures are best suited to continuous evolution--flexible and adaptable?**
- **How are enterprise architectures generated and evolved?**
- **These two issues are interdependent**
 - **Architects design enterprise architectures**
 - **Enterprise architectures influence the structure of the architects**
- **A model that rests on micro-level theory of interactions driving the operation and architecting of enterprises can help gain insight to enterprise level impact of these interactions the mechanisms and forces driving them to support enterprise design decision making**

- **Our position is that we can use narrative descriptions and technical architecture information to develop architectural representations for each conflict, measure these architectures, then characterize with a number the level of flexibility of each**
- **Hypothesis: Architectures that are lateral are more flexible than those that are vertical.**
- **Hypothesis: As constraints are placed on the enterprise, complexity increases in the form of deviations from a strict hierarchy or a lateral hierarchy. (more cross boundary violations in a vertical direction)**