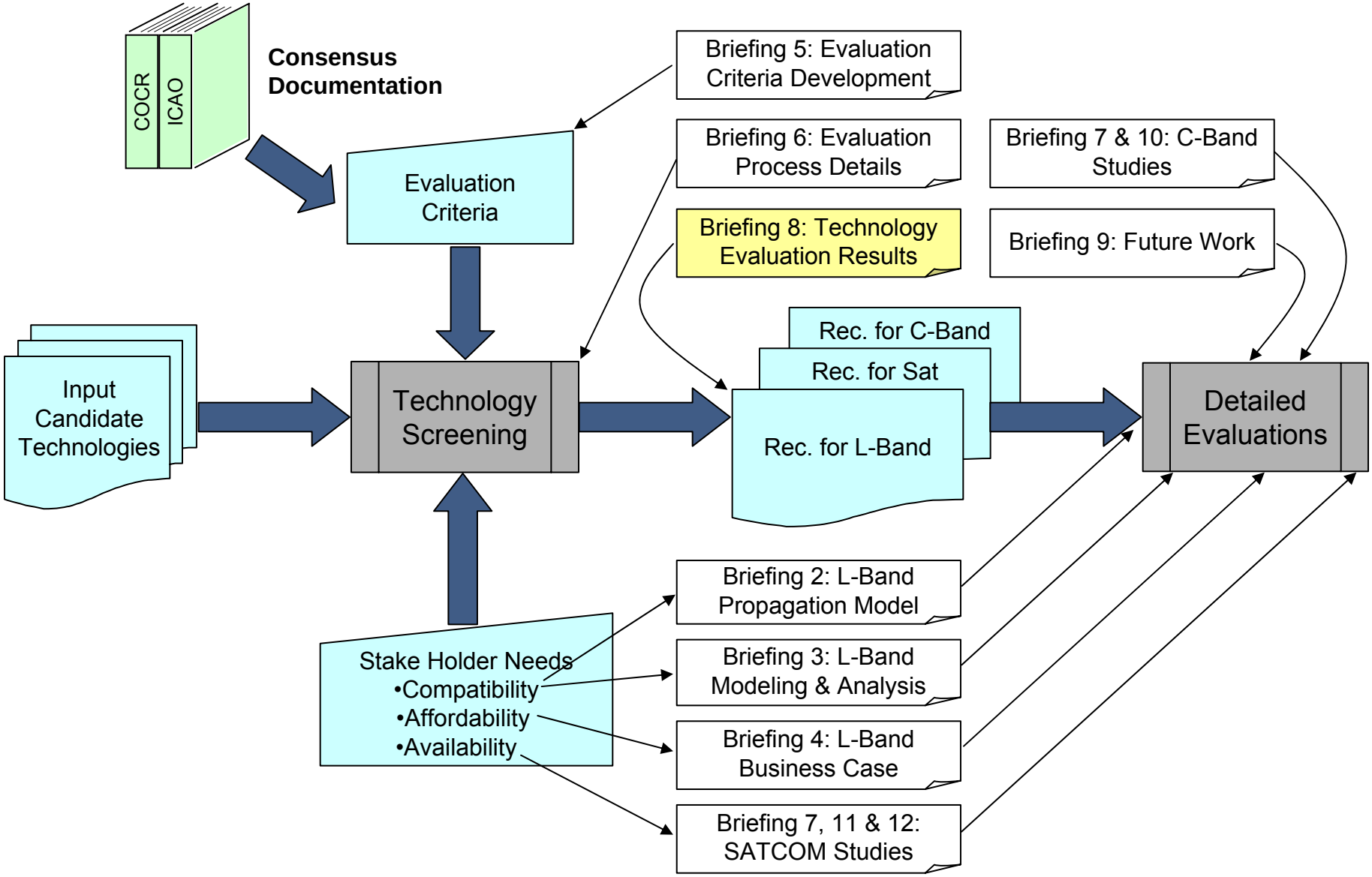
Briefing #8 – Technology Evaluation Results

Future Communications Study

Phase II End of Task Briefing

June 21, 2006

Structure and Content of the Presentations

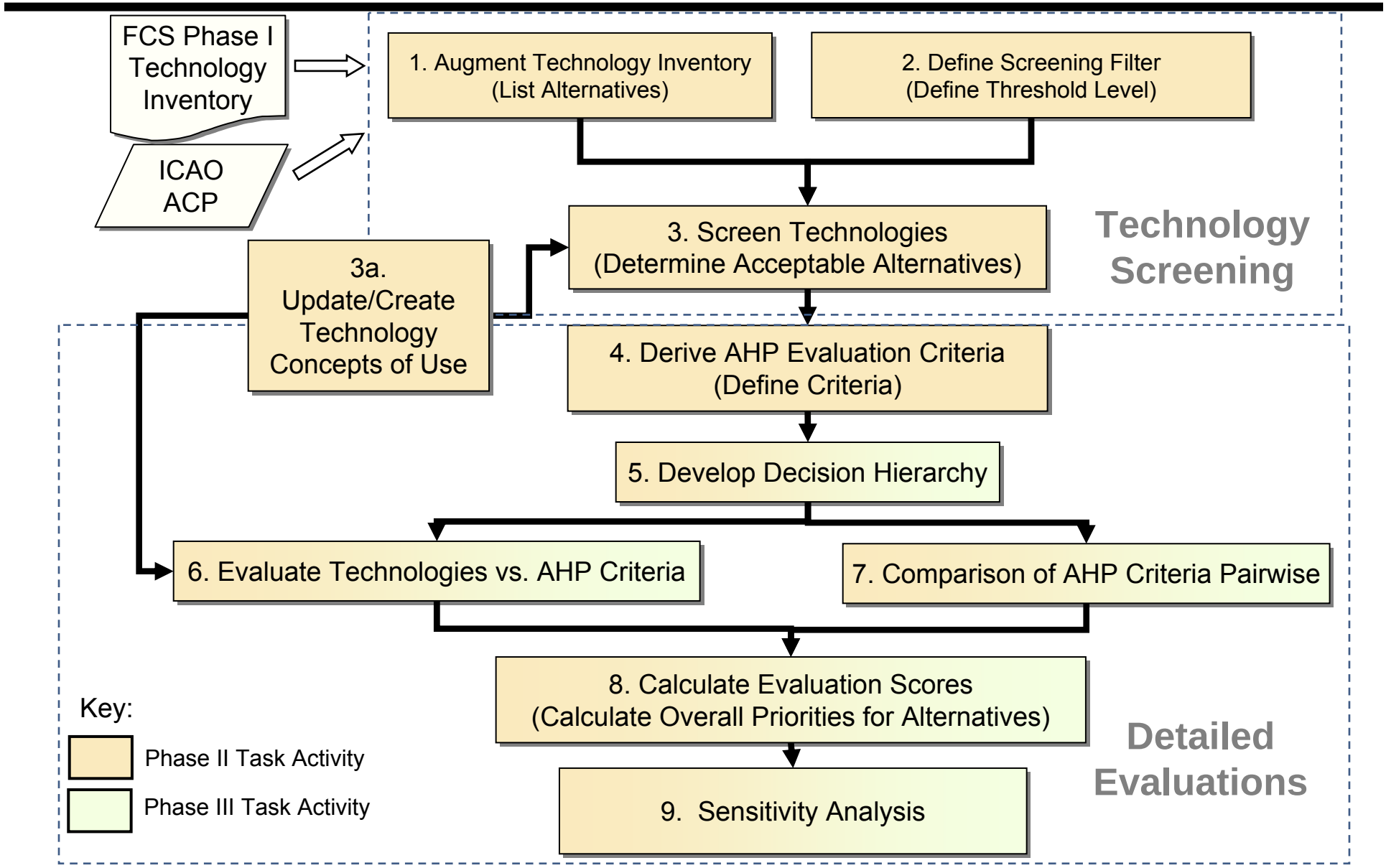


Outline

- Technology Evaluation Methodology (review)
- Technology Screening (Evaluation Steps 1 – 3)
- Detailed Evaluations (Evaluation Steps 4 – 9)
- Overview of Best Performers & Comparison to Phase I Results
- Supplemental – Technology Descriptions

Technology Evaluation Methodology (review)

Technology Evaluation Methodology



Technology Screening

Technology Screening

- We are have defined our technology screening process so that it aligns with the first three steps of the Analytical Hierarchy Process
- Recall that the first three steps of the Analytical Hierarchy Process are:
  - Step 1: Augment Technology Inventory
  - Step 2: Define Screening Filter
  - Step 3: Screen Technologies
    - Step 3A: Update/Create Technology Concepts of Use
- The next several slides describe how we applied these steps and the results from each of these steps

Step 1. Augment Technology Inventory

- The technology inventory developed during the initial technology screening task was modified to include newly considered candidate technologies within ICAO ACP for the FRS
  - L-Band E-TDMA
    - This candidate is the proposed custom narrowband E-TDMA technology band-shifted for broadband implementation (with re-designed physical layer)
  - Custom Satellite System
    - This candidate is a custom designed satellite implementation specifically designed for aeronautical communication

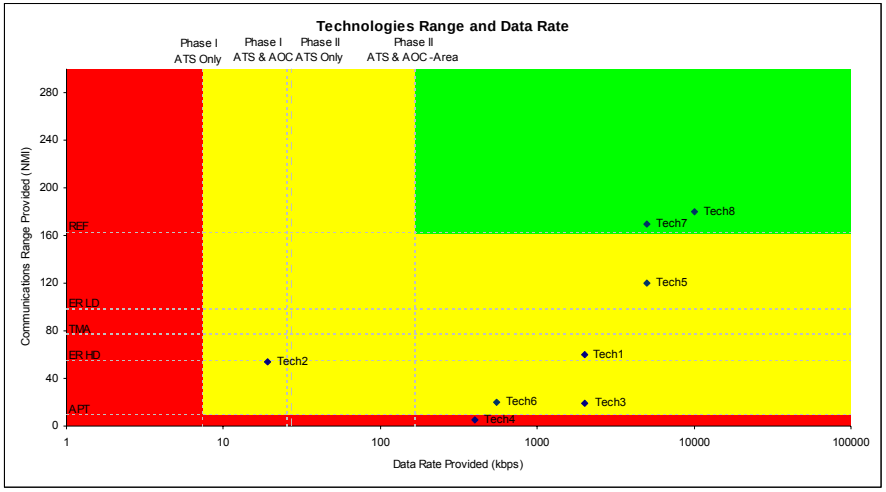
Updated Technology Inventory

Technology Family	Candidates
Cellular Telephony Derivatives	TDMA (IS-136), CDMA (IS-95A), CDMAone (IS-95B), CDMA2000 1xRTT, W-CDMA (US)/UMTS FDD (Europe), TD-CDMA (US)/UMTS TDD (Europe), CDMA2000 3x, CDMA2000 1xEV, GSM/GPRS/EDGE, TD-SCDMA, DECT
IEEE 802 Wireless Derivatives	IEEE 802.11, IEEE 802.15, IEEE 802.16, IEEE 802.20, ETSI HIPERPAN, ETSI HIPERLAN, ETSI HIPERMAN
Public Safety and Specialized Mobile Radio	APCO P25 Phase 1, APCO P25 Phase 2, TETRA Release 1, TETRAPOL, IDRA, IDEN, EDACS, APCO P34, TETRA Release 2 (TAPS), TETRA Release 2 (TEDS), Project MESA
Satellite and Other Over Horizon Communication	SDLS, Connexion by Boeing, Aero B-GAN, Iridium, GlobalStar, Thuraya, Integrated Global Surveillance and Guidance System (IGSAGS), HF Data Link, **Custom Satellite System,** Digital Audio Broadcast
Custom Narrowband VHF Solutions	VDL Mode 2, VDL Mode 3, VDL Mode 3 w/SAIC, VDL Mode E, VDL Mode 4, E-TDMA
Custom Broadband	ADL, Flash-OFDM, UAT, Mode-S, B-VHF (MC-CDMA), LDL, **E-TDMA**
Military	Link 16, SINCGARS, EPLRS, HAVEQUICK, JTRS
Other	APC Phone (Airphone, AirCell, SkyWay)

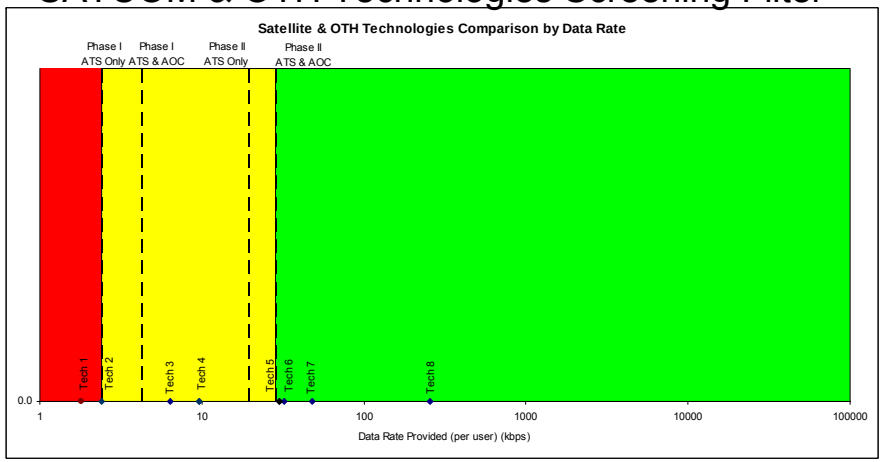
Step 2. Define Screening Filter

- The screening filter is defined to be the ability to use protected spectrum, data loading requirements, & technology communications range
  - Ability to use protected spectrum is assessed by determining if a technology inherently utilizes unprotected spectrum
  - Data loading and communication range are assess through development of a screening filter
    - Technologies are graphed according to data rate and range (for Satellite technologies only use data rate)

Terrestrial-Based Technologies Screening Filter

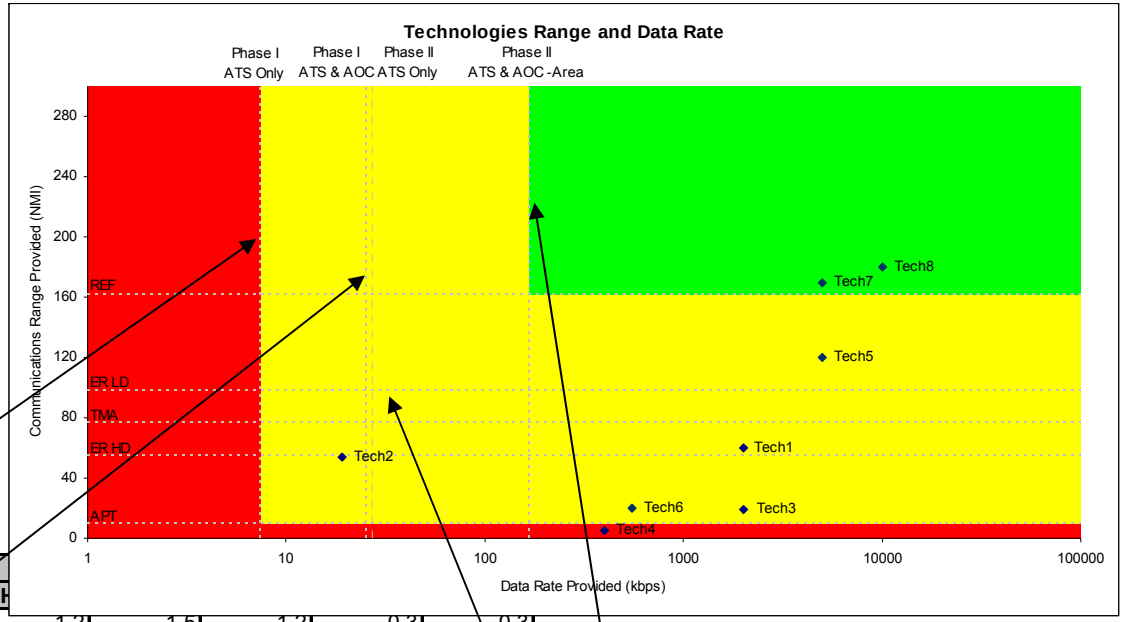


SATCOM & OTH Technologies Screening Filter



Terrestrial Filter Data Rates

- Terrestrial filter includes reference data rates extracted directly from the COCR:
  - Phase I ATS (7.4 kbps)
  - Phase I ATS & AOC (25.5)
  - Phase II ATS (27 kbps)
  - Phase II ATS & AOC (168.9 kbps)



PHASE 1		Airport SV		TMA SV						
		HD	LD	HD	LD					
Separate ATS	UL	4.0	1.2	2.3	2.2	1.2	1.5	1.2	0.3	0.3
	DL	4.3	1.9	4.1	3.9	3.7	4.9	3.7	2.7	2.2
	UL&DL	7.4	2.0	5.3	5.0	4.1	5.6	4.1	2.8	2.2
Separate AOC	UL	15.6	2.7	0.3	0.3	8.6	11.9	8.6	3.3	2.8
	DL	3.5	0.7	0.8	0.8	0.8	1.3	0.8	0.4	0.3
	UL&DL	19.9	2.9	0.8	0.8	9.1	13.8	9.1	3.3	2.8
Combined ATS&AOC	UL	18.4	2.9	2.3	2.2	9.0	12.7	8.9	3.3	2.8
	DL	6.7	2.0	4.3	4.1	3.8	5.2	3.8	2.7	2.2
	UL&DL	25.5	3.3	5.6	5.3	11.4	17.7	11.3	4.5	3.4

Table 6-19: Air/Ground Capacity Requiremen

PHASE 2		Airport SV		TMA SV AEXEC		ER SV AEXEC			OR SV AEXEC		Auto Op Area
		HD	LD	HD	LD	HD EU	HD US	LD	HD	LD	
Separate ATS	UL	12.8	7.1	22.0	22.2	20.9	22.4	21.0	19.8	19.6	7.1
	DL	11.3	5.2	10.3	10.7	9.8	13.5	10.5	8.5	8.3	13.3
	UL&DL	19.6	7.3	24.5	25.1	23.5	27.0	24.0	20.3	19.9	13.6
Separate AOC	UL	113.0	14.1	0.3	0.2	52.4	96.1	64.1	24.0	18.2	56.2
	DL	6.7	1.2	2.4	2.2	1.4	2.7	1.8	0.6	0.4	1.1
	UL&DL	131.2	14.1	2.6	2.3	58.6	106.9	72.6	24.4	18.2	62.8
Combined ATS&AOC	UL	120.0	24.6	22.0	22.2	119.1	168.3	134.8	82.1	62.8	76.7
	DL	13.4	5.4	11.1	11.8	10.2	13.9	10.9	8.6	8.3	13.4
	UL&DL	144.3	24.8	25.2	25.8	119.4	168.9	135.2	82.2	62.9	80.5

Table 6-20: Air/Ground Capacity Requirements (kbps) – Phase 2

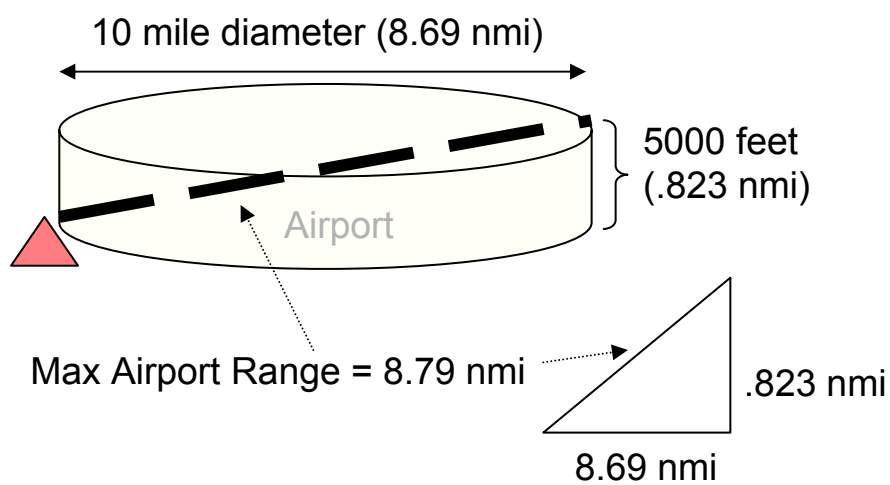
Terrestrial Filter Range Values

- Terrestrial filter range values were calculated
  - Utilized domain description information in COCR to calculate maximum communication range for each domain of interest

Airport Domain Communication Range Requirement

COCR (6.2.1): " … airport service volume equates to a cylinder 10 miles in diameter from the ground to an altitude of 5,000 feet"

Maximum range (assuming worst-case transmitter location) is approximately **9 nmi**



Terrestrial Filter Range Values (2)

- Terminal and en route range calculations were made using Phase II sector volumes defined in Section 7 of the COCR

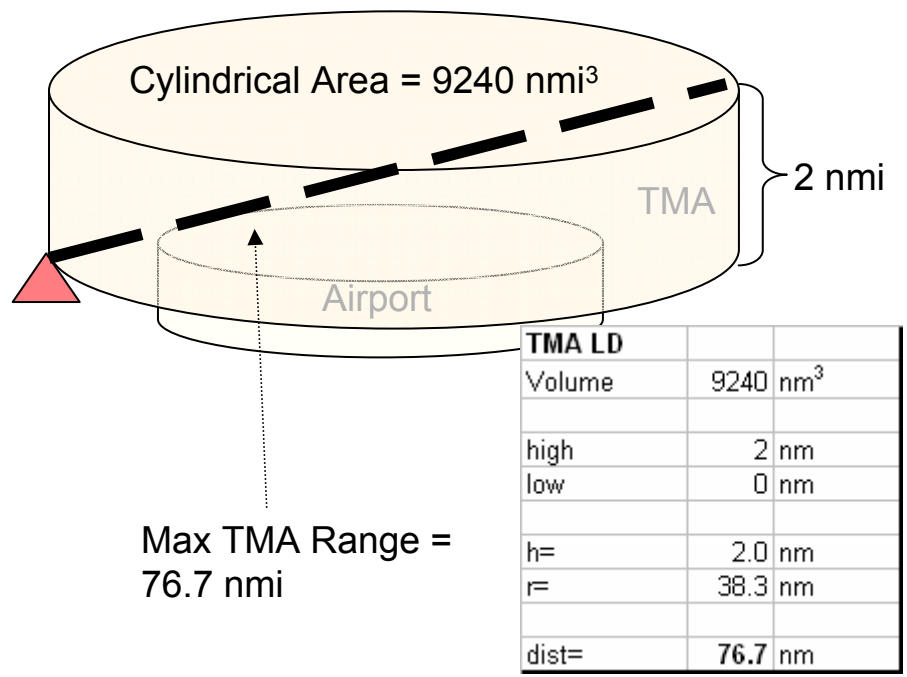
Super Sector	PIAC	Volume (NM^3)	Aircraft/NM^3
TMA LD	39	9240	0.004221
TMA HD	44	7691	0.005721
En Route LD	59	33388	0.001767
En Route HD	45	10132	0.004441

Table 7-2 Aircraft Density in Phase 2 (Super Sectors)

Terminal Domain Communication Range Requirement

The larger TMA volume specified in the COCR is used to calculate the TMA range threshold = Low Density TMA: 9240 nmi^3

Assuming a worst-case transmitter location and assuming the TMA service volume extends from the ground to a height of 2.469 nmi (approximately FL 120), the maximum coverage range can be calculated to be **76.7 nmi**



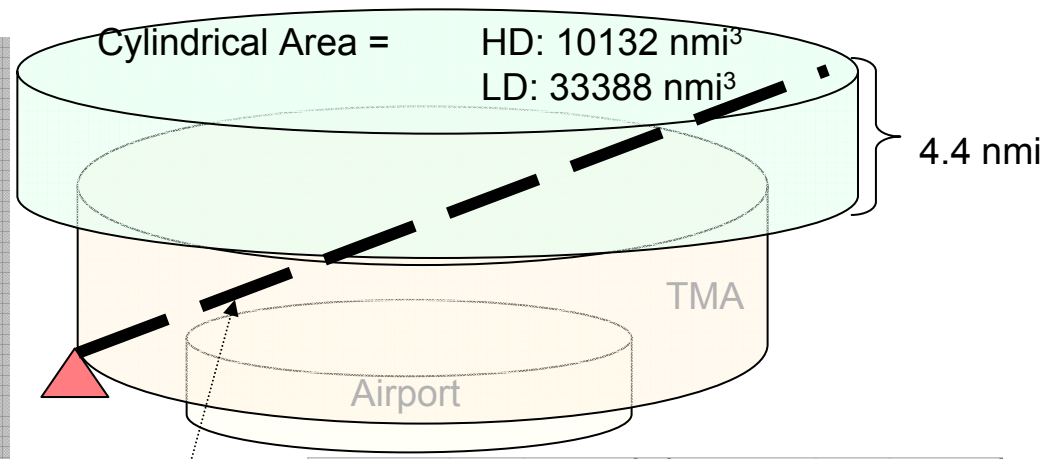
Terrestrial Filter Range Values (3)

- Due to the large variation in en route service volume definitions for low-density and high-density scenarios, two range calculations were computed for the en route domain
  - High Density TMA: 10132 nmi^3
  - Low Density TMA: 33388 nmi^3

En Route Domain Communication Range Requirement

Assuming a worst-case transmitter location assuming the ER service volume extends from from the 4.4 nmi (approximately FL 150) to a height of 7.407 nmi (approximately FL 450), the maximum coverage range can be calculated

Calculated value is **54.4 nmi** for smaller, high density sectors and **98.1 nmi** for larger, low density sectors



En Route LD		
Volume	33388	nm^3
high	45000	feet
low	18000	feet
h=	4.4	nm
r=	48.9	nm
dist=	**98.1**	nm

En Route HD		
Volume	10132	nm^3
high	45000	feet
low	18000	feet
h=	4.4	nmi
r=	26.9	nmi
dist=	**54.4**	nmi

Terrestrial Filter Range Values (4)

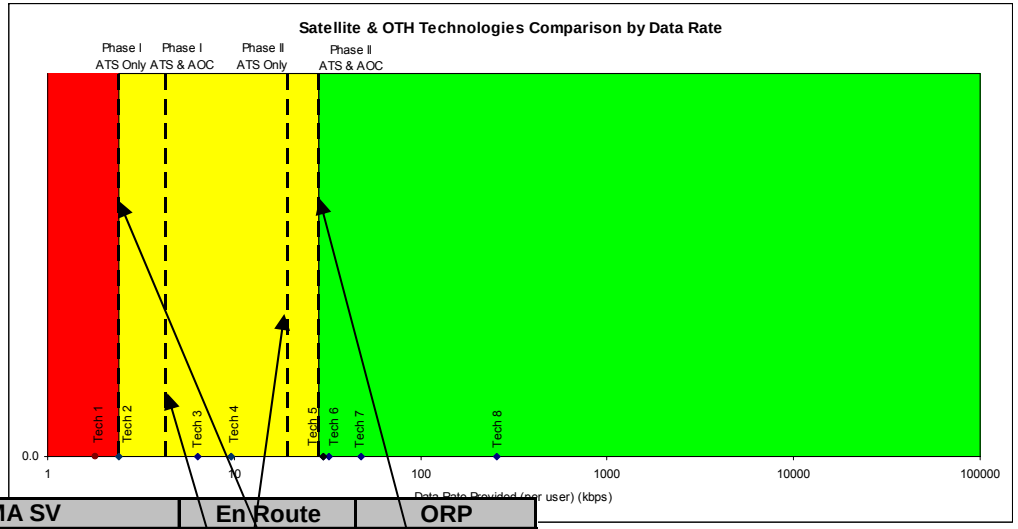
- The final communication range threshold used for the screening filter was the radio horizon reference range
  - The reference range calculated for FL180
    - To account for signal bending towards earth (especially at VHF, UHF), an approximation of the radio horizon equation is:

$$D \approx \sqrt{2h}$$

      - where h is in feet and D is in nmi
        - » For reference height of 18000 ft, equals 189.7 statue miles = 164.8 nmi
    - Used **164.8** nmi as reference range

SATCOM & OTH Filter Data Rates

- SATCOM filter includes reference per-user data rates extracted directly from the COCR:
  - Phase I ATS (2.5 kbps)
  - Phase I ATS & AOC (4.3 kbps)
  - Phase II ATS (19.7 kbps)
  - Phase II ATS & AOC (28.7 kbps)



PHASE 1		Airport SV		TMA SV		En Route	ORP
		Dep	Arr	Dep	Arr	SV	SV
Separate ATS	UL	1.1	0.7	0.6	1.5	0.9	0.3
	DL	1.8	0.7	1.9	0.8	2.4	1.7
	UL&DL	1.8	0.7	2.0	1.5	2.5	1.7
Separate AOC	UL	2.4	0.2	0.2	0.2	4.3	2.4
	DL	0.3	0.3	0.3	0.3	0.3	0.3
	UL&DL	2.4	0.3	0.3	0.3	4.3	2.4
Combined ATS&AOC	UL	2.4	0.7	0.6	1.5	4.3	2.4
	DL	1.8	0.7	1.9	0.8	2.5	1.7
	UL&DL	2.4	0.7	2.0	1.5	4.3	2.5

Table 6-22: Air/Ground C

PHASE 2		Airport SV		TMA SV		En Route	ORP	AOA
		Dep	Arr	Dep	Arr	SV	SV	
Separate ATS	UL	6.9	1.8	19.5	19.5	19.5	19.4	6.7
	DL	6.2	1.9	6.8	3.3	6.7	8.5	12.5
	UL&DL	6.9	1.9	19.7	19.5	19.5	19.5	12.5
Separate AOC	UL	9.2	0.2	0.2	0.2	20.4	12.1	12.6
	DL	0.3	0.3	0.4	0.4	0.3	0.3	0.3
	UL&DL	9.2	0.3	0.4	0.4	20.4	12.1	12.6
Combined ATS&AOC	UL	9.2	1.8	19.5	19.5	28.6	25.4	12.7
	DL	6.2	1.9	6.8	3.4	6.7	8.5	12.5
	UL&DL	9.5	1.9	19.8	19.5	28.7	25.4	17.0

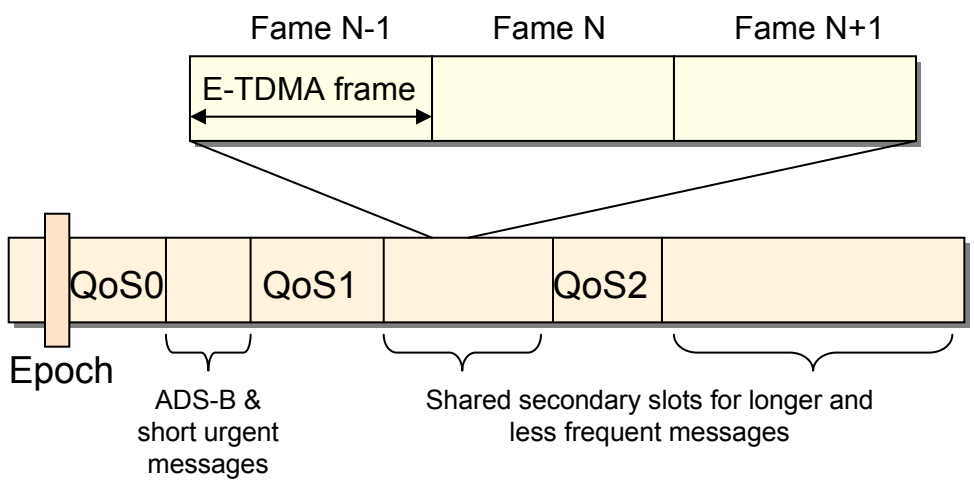
Table 6-23: Air/Ground Capacity Requirements (kbps) for Each Aircraft usign A Separate 'Channel' – Phase 2

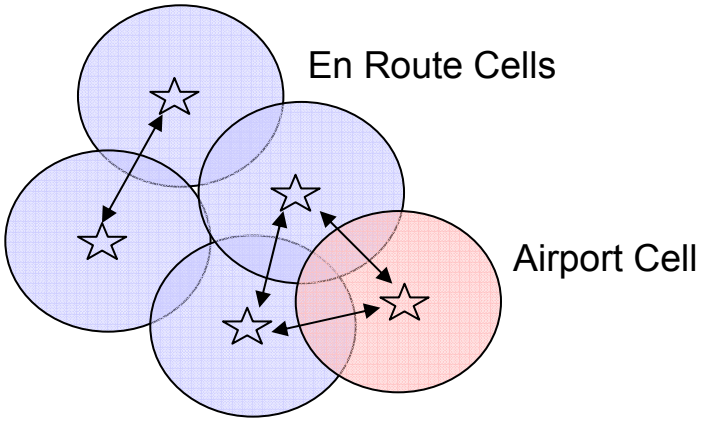
Step 3A. Update/Create Technology Concepts of Use

- Major focus was development of new concepts of use for technologies added to technology inventory
  - Includes L-band E-TDMA and Custom Satellite System
- Additionally, aeronautical communication concepts developed for other technologies that had been part of the initial technology screening (2004) were reviewed
  - Ensured that concepts reflect stakeholder input to focus on data-only solutions
  - Ensured that technology advancements over the past two years have been addressed

L-band E-TDMA Overview

- Statistical Self-Synchronization TDMA frame structure in a cellular layout
  - Global ground coordination not required
  - TDMA frame structure includes:
    - Unconditional access for every mobile in an exclusive primary slot in every frame
    - Reservation-based access to pools of secondary slots
  - Deterministic MAC sublayer
  - Self-insertion rather than cellular handover
- Available literature describes technology at a high layer
  - Detailed physical layer, MAC layer description and parameter values have not been identified in published documentation





Custom Satellite System Example

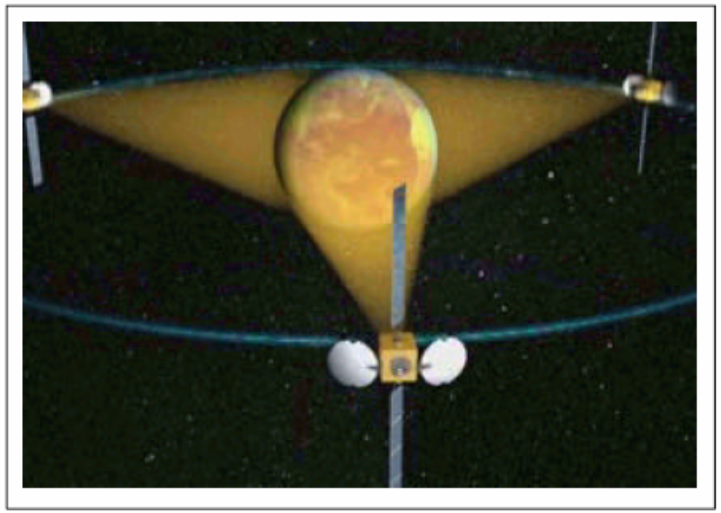


Figure 1 : SDLS Concept
(from "SDLS Slice 3 – Executive Summary", SDLS-ASP-SP-0031, SDL3 Slice 3 Consortium, Feb 2004)

- This is a general technology definition to address a space-based architecture for air traffic control
  - Examples of specifications and systems include:
    - SDLS (European Space Agency initiative)
      - Bent-pipe geostationary satellites and CDMA at L- Band
      - Design goals are low cost infrastructure and low operational costs
    - Japan's Multi-function Transport Satellite (MTSAT)
      - Primary/back geostationary satellites
        - » Provide GPS augmentation and bent-pipe A/G communication services

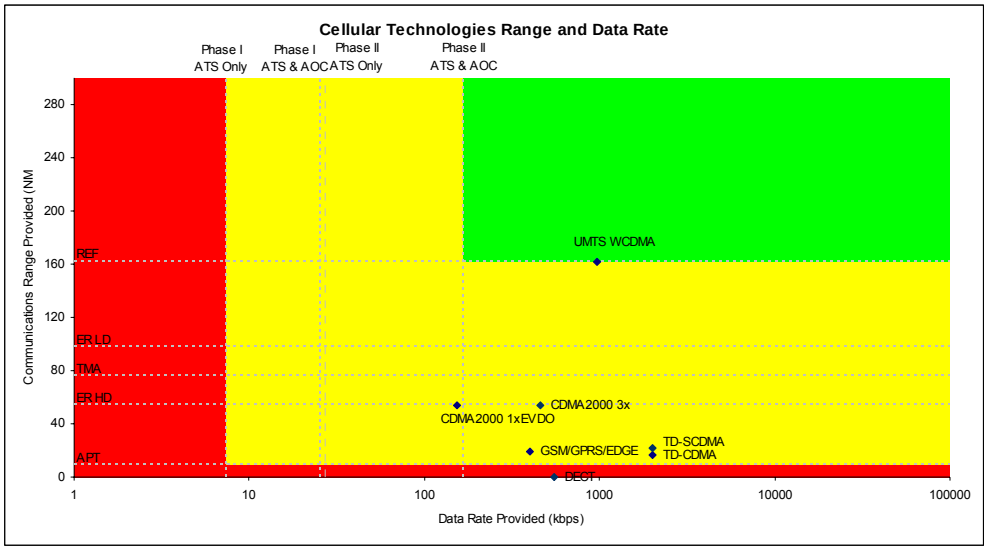
Example CONUSE Updates

- Cellular Telephony
  - Identified data rates for modulation/coding pairs that provide lower BER performance (e.g. BPSK/QPSK rather than 64-QAM)
  - Refined maximum range calculations
- Custom Broadband Solutions
  - Refined UAT and Mode S data rate estimates to reflect data throughputs rather than burst data rates
- Military Communications
  - Modified Link 16 time-slot allocation scheme to “dedicated access” to reflect data-specific data rate/latency requirements

Step 3. Screen Technologies

- To screen technologies, technologies were first reviewed to determine their ability to use protected spectrum
  - Digital Audio Broadcast, Connexion, and APC Telephony technologies did not pass this filter
- Next, the screening filter (data rate and range (as applicable)) was applied on a technology family-by-technology family basis
  - This supported identification of “best performers” within each technology family

Step 3. Screen Technologies (2)



Cellular Technologies

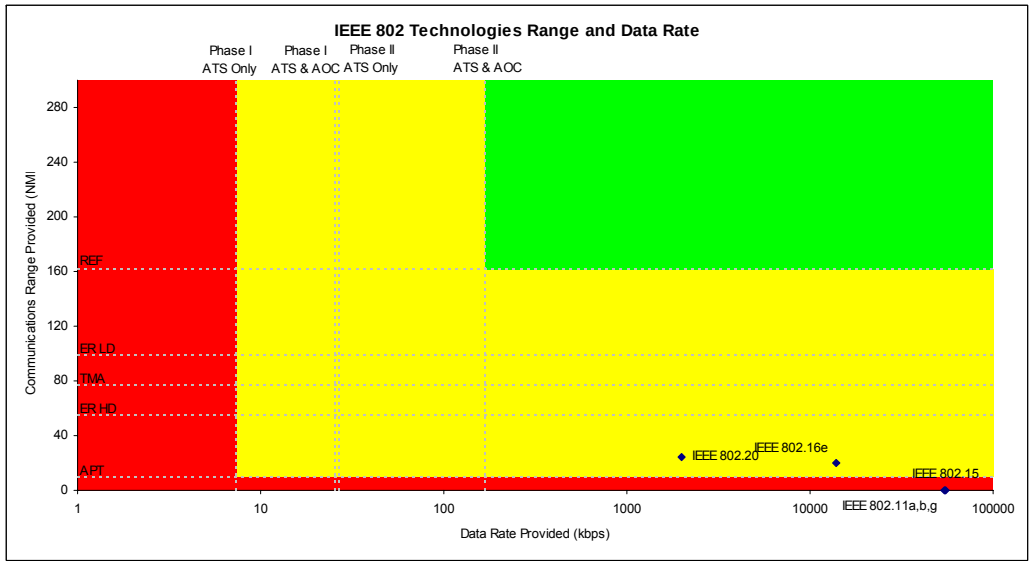
All technologies within this family perform well with respect to offered capacity; however many of the technologies have very small communication range definitions. The technologies with limited range capability would only be applicable as cost effective solutions in the airport domain

Only UMTS W-CDMA is a viable candidate as a general aeronautical communication solution

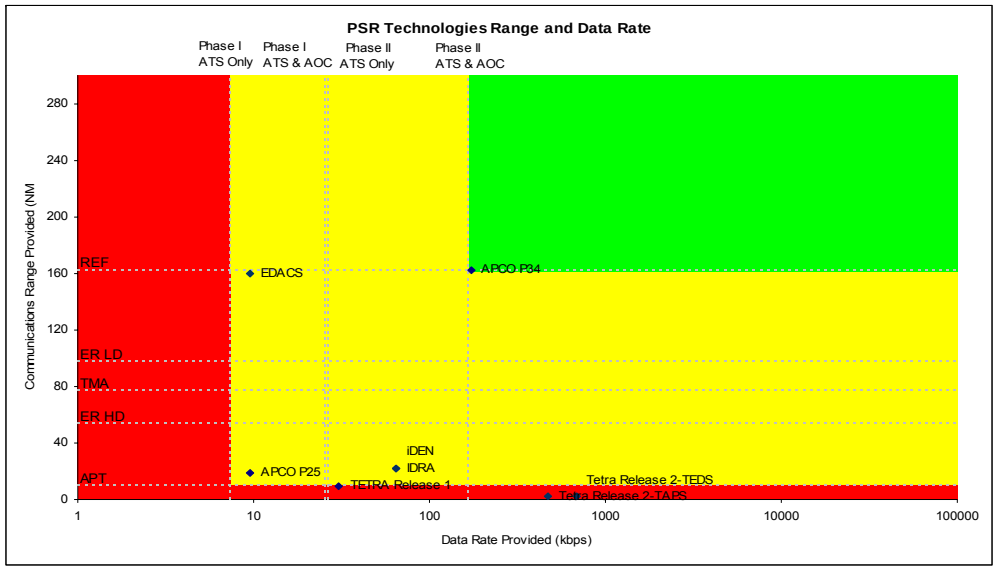
IEEE 802 Technologies

Similar to cellular technologies, the technologies within this family perform well with respect to offered capacity. There are no technologies that provide sufficient range to be considered a cost effective general aeronautical communication solution

These technologies can only be considered as viable solutions within the context of the airport domain



Step 3. Screen Technologies (3)



PSR Technologies

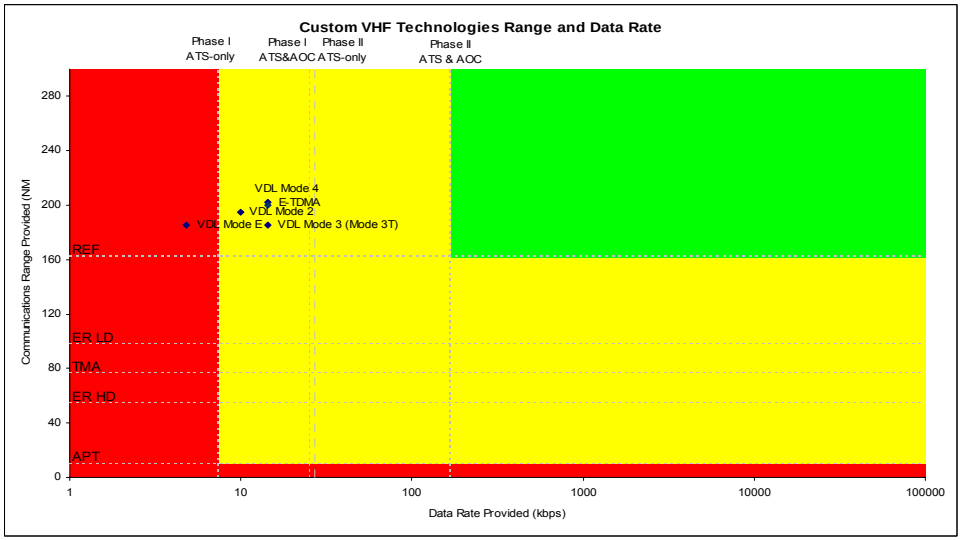
A large number of technologies within this family perform well with respect to offered capacity; however, many of the technologies are have very small communication range definitions.

EDACS can provide sufficient communication range; however, offered data rate is only slightly above the minimum Phase I requirements

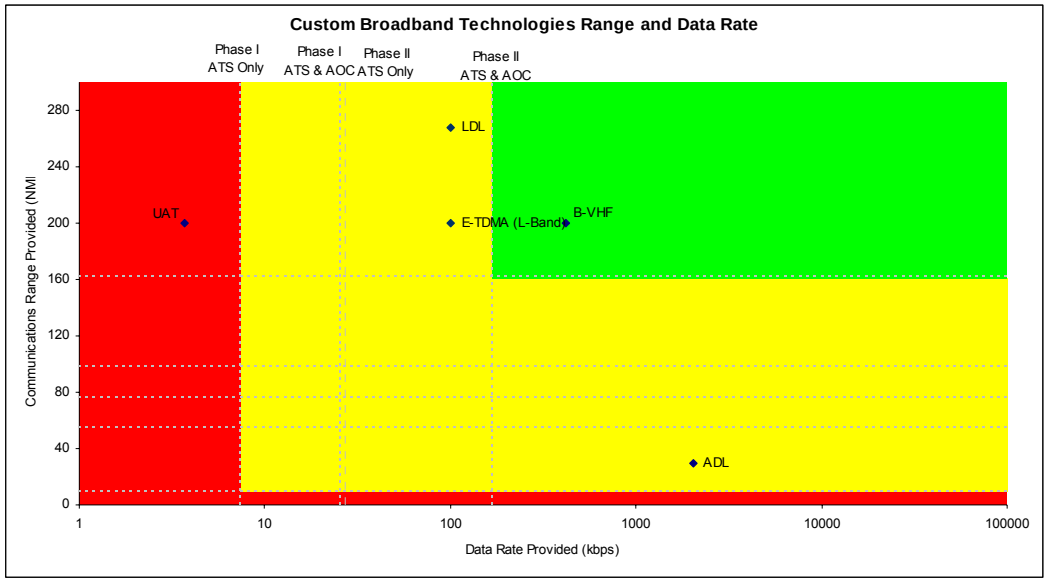
APCO P34 is a viable candidate as a general aeronautical communication solution as it offers sufficient data rate and range to provide a long-term solution

Custom VHF Technologies

All technologies within this family provide sufficient range to be considered a cost effective general aeronautical communication solution. Although many provide sufficient data rates to accommodate Phase I traffic requirements, none can accommodate Phase II traffic requirements, even ATS-only requirements. Since the FAA roadmap indicates that the US will only field the FRS as a consequence of insufficient data rate of VHF technologies, it did not seem appropriate to consider these technologies further.



Step 3. Screen Technologies (4)



Custom Broadband Technologies

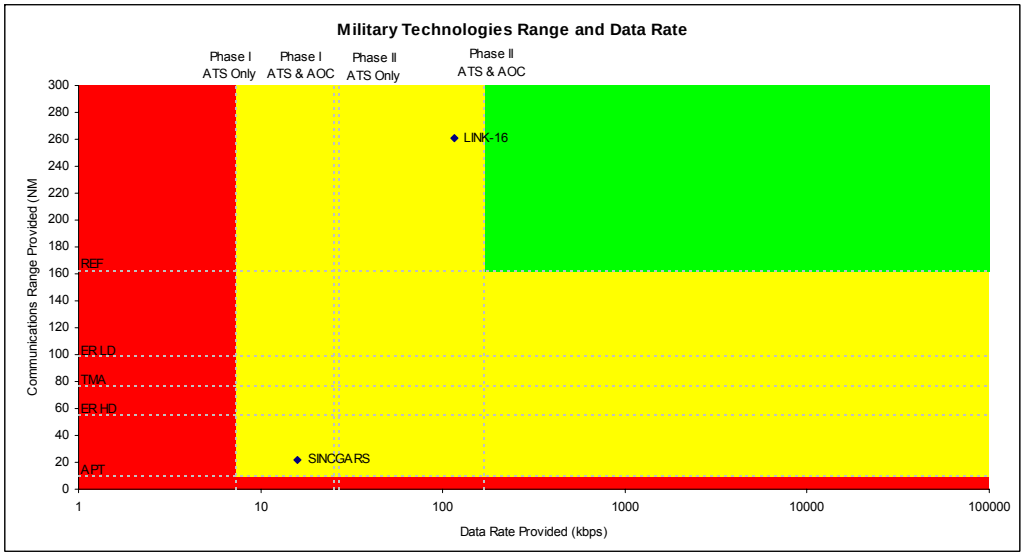
There are two general categories of results within this technology family. LDL, E-TDMA and B-VHF all provide or come close to providing required data rates. B-VHF meets all requirements while LDL and E-TDMA exceed Phase II ATS only requirements. All provide sufficient communication range to be viable general solutions.

UAT and ADL are not viable general solution technologies

Military Technologies

Link 16 performs well in both data rate and communication range. This technology exceeds all communication range references, meets Phase II ATS only data rate requirements and comes close to meeting all data rate requirements. It was brought forward from the screening.

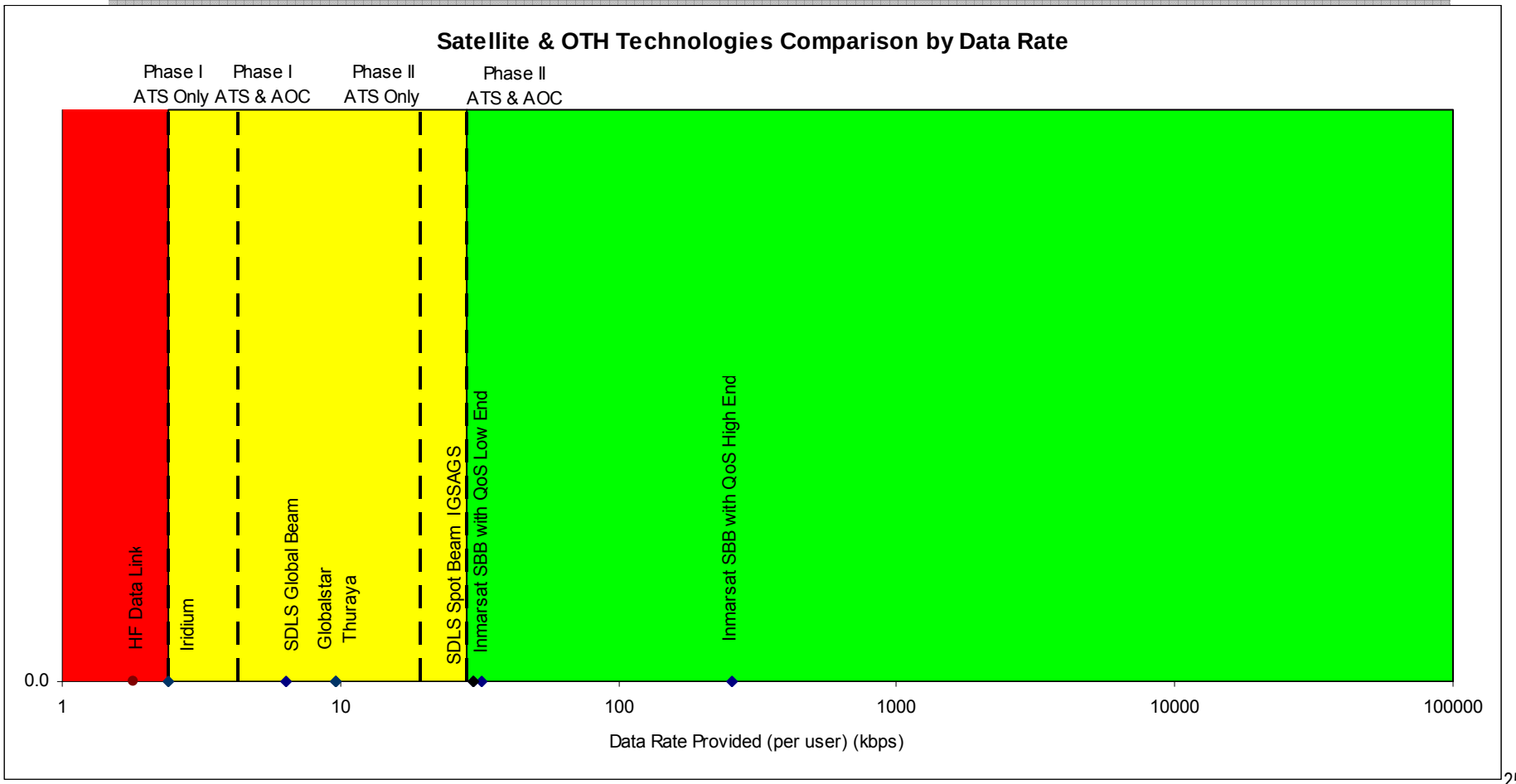
SINGARS does not offer sufficient data rate or range to be considered a viable general solution candidate



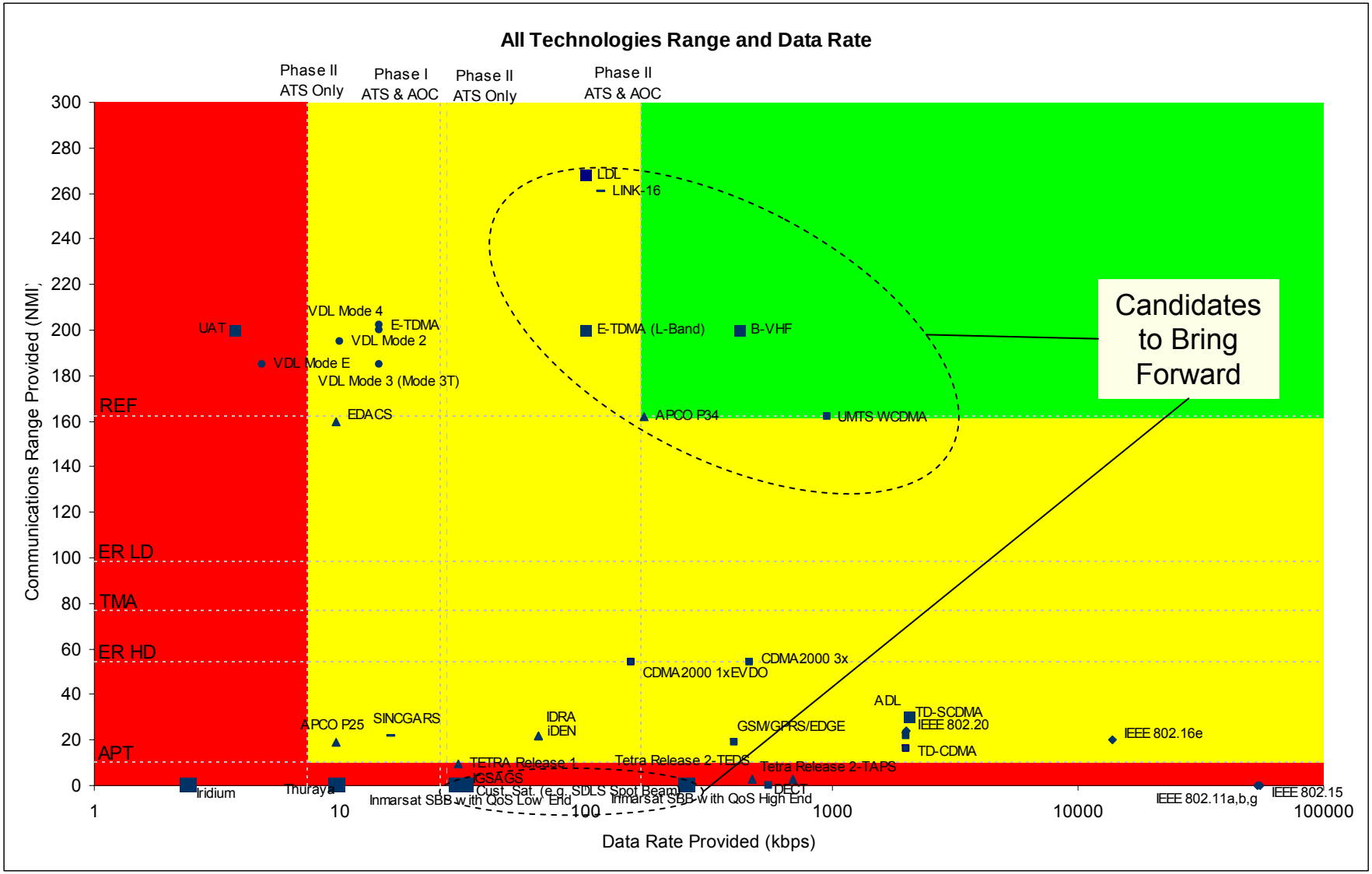
Step 3. Screen Technologies (5)

Satellite and OTH Technologies

Inmarsat SBB and the Custom Satellite System all meet the per-user data rate requirements for both Phase II ATS only traffic as well as Phase II ATS and AOC combined traffic. Although some other candidates here score in the yellow zone, they do not provide the required per-user data rate to meet the Phase II ATS requirements, and thus have limited capability for Phase II. Inmarsat SBB and Custom Satellite System are the candidates brought forward in the screening from this technology family.



Technology Screening Summary



Technology Short List

	Pre-Screened Technologies
Continental Solution	W-CDMA P34 Inmarsat Custom Satellite System (e.g. SDLS) E-TDMA LDL B-VHF Link 16
Oceanic Domain	Inmarsat Custom Satellite System (e.g. SDLS)
Airport Domain	IEEE 802.16

- Eight technologies are brought forward from the Screening process
  - These are candidates to provide a general solution applicable to continental airspace (including en route, TMA and airport)
  - These candidates are considered further as part of a full technology investigation
- In addition to a general communication solution, some technologies can be considered in the context of specific domains
  - Some domains, such as the oceanic domain, have a unique environment that warrant separate technology consideration

Comparison to EUROCONTROL Short List

- Eurocontrol presented their current technology short list at the ICAO ACP WG-C10 meeting (March 17, 2006)

	Technology Short List
Evolution of existing aeronautical systems or concepts	• (x) DL3 • E-TDMA • (x) DL4
New terrestrial systems	• B-VHF • 3G systems (WCDMA) • P34
Satellite Systems	• Inmarsat SwiftBroadband • New satellite system(s)
Airport/surface systems	• 802 derivatives .11x, .16 and .20 • Airport Data Link

Comparison to EUROCONTROL Short List (2)

NASA/ITT Recommendations	*Common Recommendations*		Eurocontrol Recommendations
Continental	W-CDMA P34 E-TDMA LDL [(x)DL3] B-VHF	W-CDMA P34 E-TDMA LDL [(x)DL3] B-VHF	**Continental** (x)DL4
Oceanic Inmarsat SBB Custom Satellite	Inmarsat SBB Custom Satellite	Inmarsat SBB Custom Satellite	**Oceanic**
Airport	IEEE 802.16	IEEE 802.xx	**Airport** ADL

Detailed Evaluations

Detailed Evaluations

- Detailed technology evaluations address steps 4 – 9 of the Analytical Process Hierarchy
  - Step 4: Derive AHP Evaluation Criteria
  - Step 5: Develop Decision Hierarchy
  - Step 6: Evaluate Technologies vs. AHP Criteria
  - Step 7: Comparison of AHP Criteria Pairwise
  - Steps 8/9: Calculate Evaluation Scores & Sensitivity Analysis

Step 4. Derive AHP Evaluation Criteria

- Briefing 5 described the derivation of evaluation criteria
  - Technical criteria (derived from the COCR)
  - Institutional criteria (derived from ICAO consensus documents)
- These are defined to be the AHP evaluation criteria

Derived Technical Criteria

- Functional Criteria
  - Meets ATC Needs
    - A/G & G/A Addressed in APT, TMA, ENR, ORP & AOA Domains
    - Ground Originated Broadcast in APT, TMA, ENR, ORP & AOA Domains
    - A/A Addressed in TMA & AOA Domains
  - Meets AOC Needs
    - A/G & G/A Addressed in APT, TMA, ENR, ORP, & AOA Domains
- Performance Criteria
  - Data Rate
  - Number of Users
  - Quality of Service
  - Latency

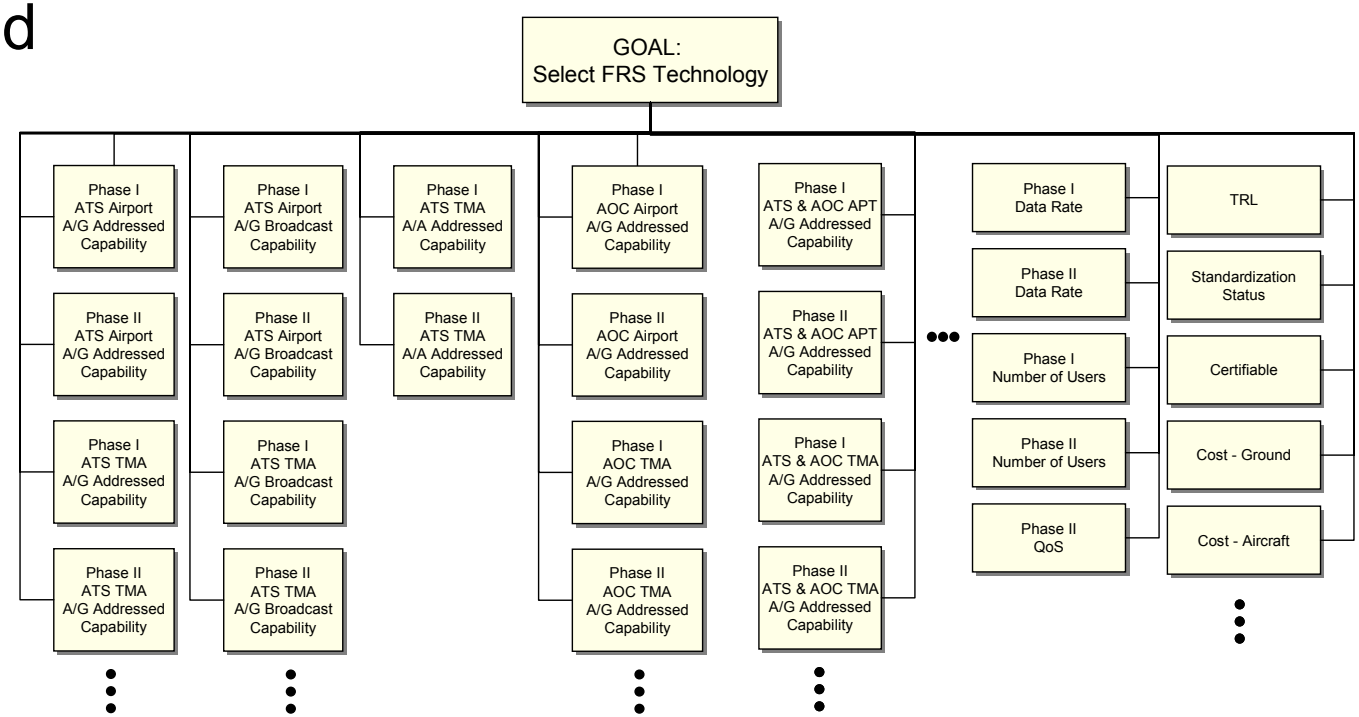
Derived Institutional Criteria

- Maturity for Aeronautical Environment
  - Technical Readiness Level
  - Standardization Status
  - Certification Issues
- Cost
  - Ground Infrastructure
  - Avionics equipage
- Safety and Security
  - Spectrum Protection
  - Security – Authentication and Integrity
  - Security – Robustness to Deliberate RF Interference
- Transition
  - Return on partial investment
  - Ease of technical migration (spectral, physical)
  - Ease of operational migration (air and ground users)

Step 5. Develop Decision Hierarchy

- The next step in AHP is the definition of the Decision Hierarchy
  - It is composed of evaluation criteria or groups of evaluation criteria combined into a single decision factor
- A decision hierarchy that incorporates each derived criterion as a top-level decision factor was explored and quickly discarded

A representation of a decision hierarchy that accommodates each unique evaluation criteria as a Level-1 decision factor



Step 5. Develop Decision Hierarchy (2)

- Exploring the creation of technical criteria decision factors
  - Five categories of components make up technical criteria

	Evaluation Criterion	Functional Capability	Capacity (C) & Performance (P)
1	Meets ATS Data Link Needs	**A. A/G & G/A Addressed** – Airport, TMA, En Route, Oceanic/Remote, Polar, Autonomous Zone	***C1***: Data Rate ***C2:*** Number of Users ***P1***: Priority Levels/QoS ***P2:*** Latency
		B. G/A Broadcast – Airport, TMA, En Route, Oceanic/Remote, Polar, Autonomous Zone	
		C. A/A Addressed – Airport, TMA, En Route/Autonomous, Oceanic/Remote, Polar	
2	Meets AOC Data Link Needs	**A. AOC Data –** Airport, TMA, En Route/Autonomous, Oceanic/Remote/Polar	

Not all permutations are valid (e.g. AOC G-A Broadcast); There are 336 valid permutations

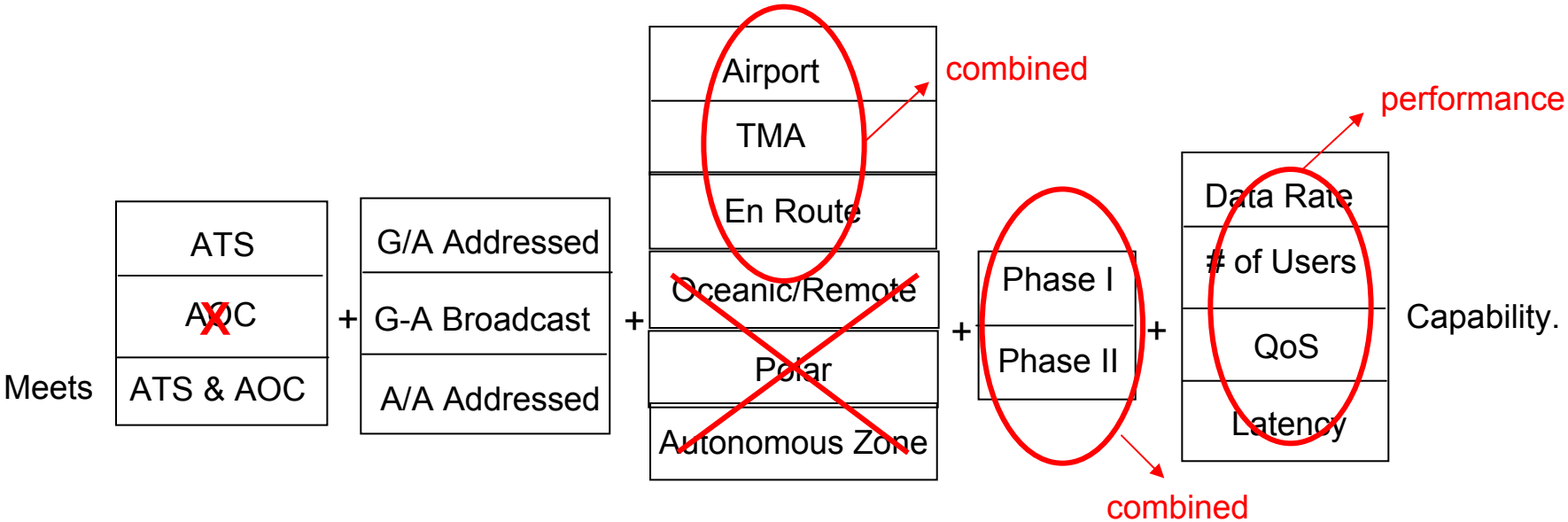
ATS	+	G/A Addressed	+	Airport	+	Phase I	+	Data Rate
AOC		G-A Broadcast		TMA		Phase II		# of Users
ATS & AOC		A/A Addressed		En Route				QoS
				Oceanic/Remote				Latency
				Polar				
				Autonomous Zone				

Step 5. Develop Decision Hierarchy (3)

- Observations on the technical criteria structure (shown in previous slide)
  - Distinction of Phase I/Phase II is not necessary
    - For the FCS roadmap, implementation of a new technology in support of the FCS is in the 2020 + timeframe (focus on Phase II)
  - Focus of FCS is not provisioning of an AOC-only service
  - Flight Domains do not provide a meaningful discriminator between technologies
    - Technologies that can meet oceanic/remote/polar domain requirements are limited to SATCOM & HF – we already know there is no “silver bullet” – no need to bias results in considering these domains
    - Technologies with limited communications range that provide high data rates have been nominated as candidates for the airport surface
      - Clearly, an airport-only solution is not the scope of the FRS
    - The distinctions above can be made outside of full technology comparison/evaluation

Step 5. Develop Decision Hierarchy (4)

- Apply noted observations
  - Remove AOC-only, O/R/P domains, and Operational Phase distinction from consideration
  - Combine Airport, TMA, and en route into a defined "continental" airspace domain
  - Combine performance requirements
- Level-1 decision factors for technical criteria are defined for remaining permutations



Step 5. Develop Decision Hierarchy (5)

- A simplified view of the remaining technical criteria components used to generate top-level decision factors:

Meets | ATS / ATS & AOC | + | G/A Addressed / G-A Broadcast / A/A Addressed | Functionality and Performance.

With this refined set of inputs, there are 6 valid permutations

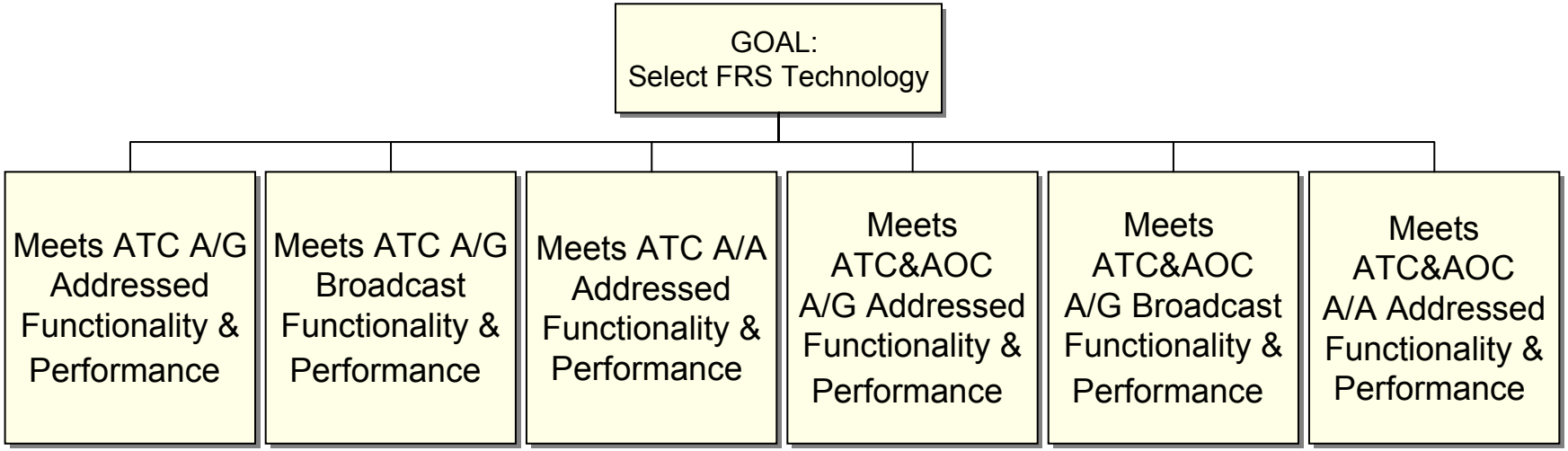
- Sample decision factor definition:

Meets | ATS / ATS & AOC | + | G/A Addressed / G-A Broadcast / A/A Addressed | Functionality and Performance

Meets ATS G/A Addressed Functionality and Performance

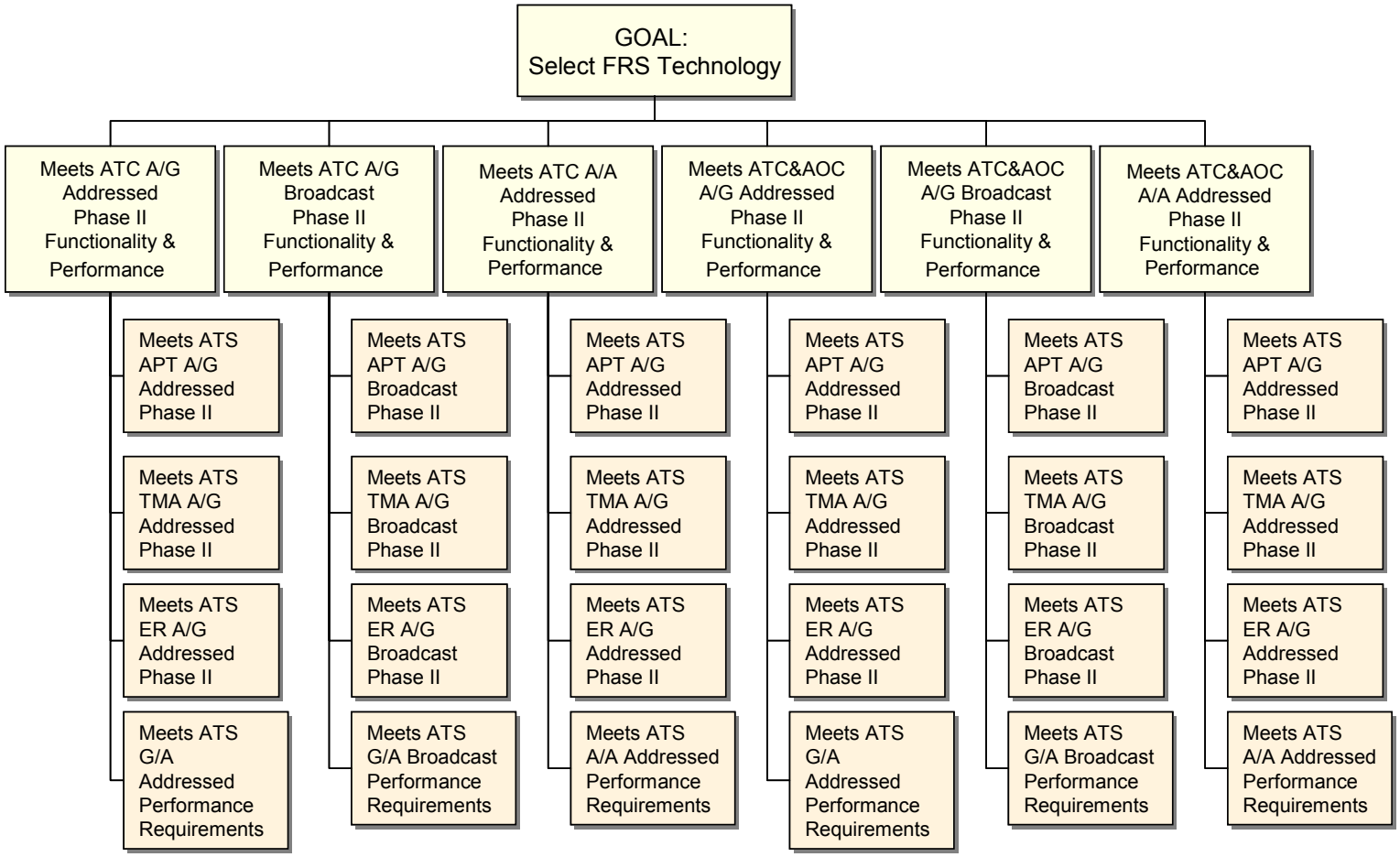
Step 5. Develop Decision Hierarchy (6)

- Overview of Technical Criteria Level-1 Decision factors



Step 5. Develop Decision Hierarchy (7)

- To illustrate traceability to individual derived technical criteria, the decision hierarchy can be decomposed (second-level decomposition shown)

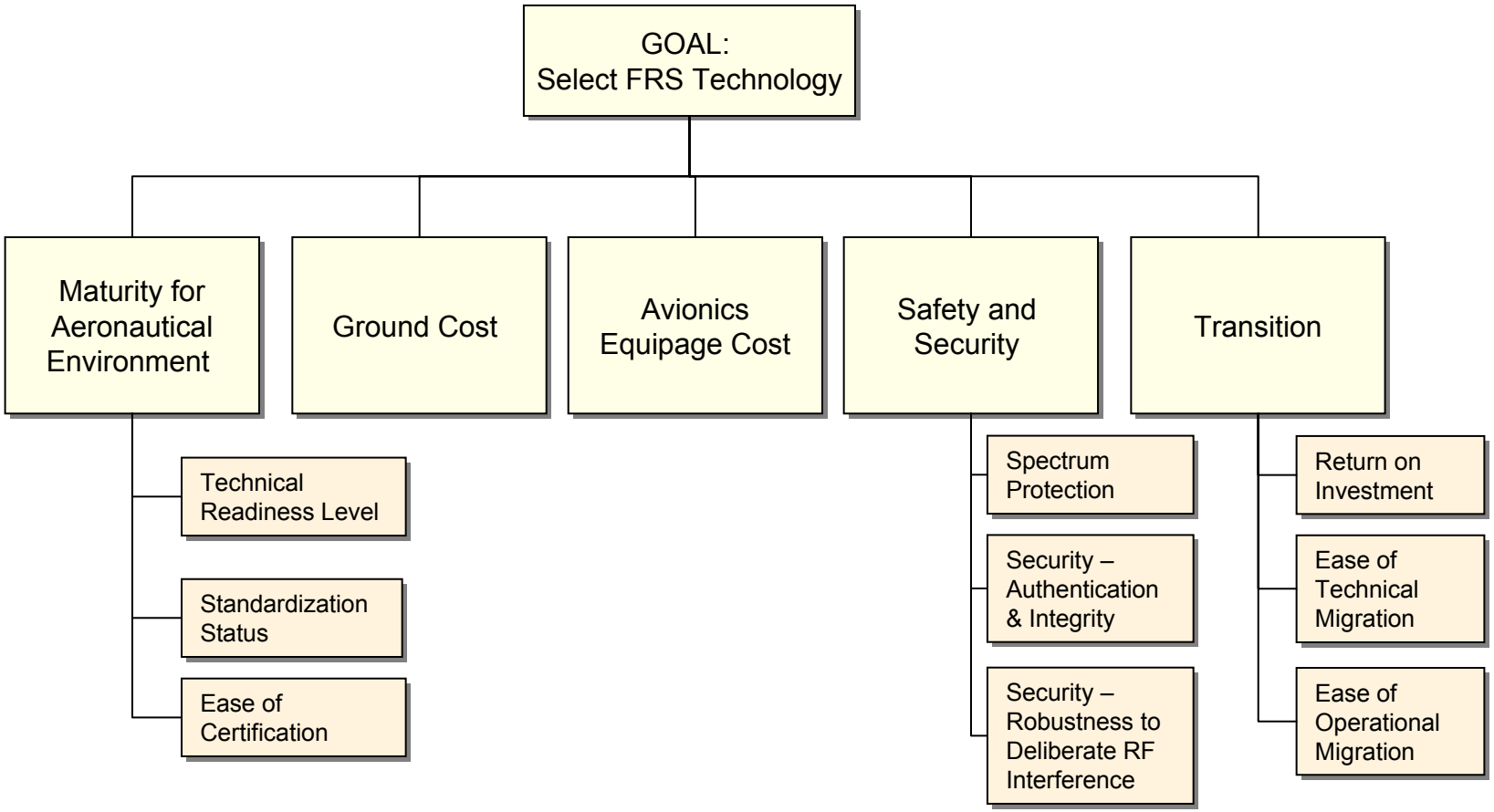


Step 5. Develop Decision Hierarchy (8)

- Deriving Level-1 decision factors from derived technical criteria
  - The nine derived institutional criteria were combined into five major categories
    - Supported roll-up of criteria that address common topics
    - Level-1 factors include:
      - Maturity for aeronautical communications
      - Ground Cost
      - Avionics Equipage Cost
      - Safety and Security
      - Transition

Step 5. Develop Decision Hierarchy (9)

- Overview of Technical Criteria Level-1 Decision factors (and associated decomposition)



Step 5. Develop Decision Hierarchy (10)

- Full Set of Decision Hierarchy Level-1 Decision Factors:

	Level -1 Decision Factors
1	Meets ATS_G-A-Addressed_COCR Requirements
2	Meets ATS_G-A-Broadcast_COCR Requirements
3	Meets ATS_A-A-Addressed_COCR Requirements
4	Meets ATS&AOC_G-A-Addressed_COCR Requirements
5	Meets ATS&AOC_G-A-Broadcast_COCR Requirements
6	Meets ATS&AOC_A-A-Addressed_COCR Requirements
7	Provides highly mature technical solution
8	Provides low ground infrastructure cost solution
9	Provides low avionics installation cost solution
10	Provides highly secure/safe solution
11	Provides low-risk/low complexity service provider transition

Step 6. Evaluate Technologies vs. AHP Criteria

- A two step process was used to evaluate technologies against AHP Criteria (e.g. Level-1 decision factors)
  - First, technologies were scored against the evaluation criteria
  - Recall that some “Decision Factors” are a combination of evaluation criteria
    - Example – The “Maturity for Aeronautical Environment” Decision Factor is a combination of the “Technical Readiness Level”, “Standardization Status” and “Ease of Certification” evaluation criteria
  - Consequently, a mechanism to combine individual scores against evaluation criteria to determine the score for decision factors was defined

Step 6. Evaluate Technologies vs. AHP Criteria (2)

- To perform the first step in the evaluation, concept of use material was used to build a matrix of key technology parameters

Technology Family	**Cellular**	**PSR**	**Satellite**	**Satellite**	**Custom VHF**	**Custom Broadband**				**Military**	**IEEE 802**
	WCDMA	P34	INMARSAT	tellite System	VDL M3T	E-TDMA	LDL	B-VHF	UAT	LINK-16	IEEE 802.16e
Flight Domain											
APT	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
TMA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
ENR	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
OR	No	No	Yes	Yes	No	No	No	No	Yes	No	No
P	No	No	No	No	No	No	No	No	Yes	No	No
AOA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Functionality											
A/G & G/A Addressed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Ground Originated Broadcast	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
A/A Addressed	No	Yes	No	No	No	Yes	No	Yes	No	Yes	Yes
Air Originated Broadcast	No	Yes	No	No	No	Yes	No	Yes	Yes	Yes	Yes
Data Rate (kbps)											
Data Rate for ATS (kbps)	960	173	32	30	14.4	100	100	421.2	3.712	115	13800
Data Rate for ATS+AOC (kbps)	960	173	32	30	14.4	100	100	421.2	3.712	115	13800
Max Number Users	552	512	2445	2500	180	512	512	1000	1000	64	1000
Max Number of Users (ATS-only for area-based a	N/A	N/A	5085	2500	N/A	N/A	N/A	N/A	N/A	N/A	N/A
QoS	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Latency	Yes	Yes	Yes	Yes		Yes	Yes	Yes	No	Yes	Yes
Average Coverage Area Volume (per area) (nm^3)	N/A	N/A	1335235		N/A	N/A	N/A	N/A	N/A	N/A	N/A
Technical solution maturity	0	1	1	1	1	0	1	0	1	0	0
Technical Readiness Level	2	1	2	1	2	0	1	0	2	2	2
Standardization Status	1	1	1	1	2	0	1	0	2	0	1
Certifiability	0	1	1	1	2	2	2	1	2	1	0
Ground infrastructure cost solution	0	1	1	0	1	1	1	1	1	0	2
Avionics installation cost	2	2	1	2	2	2	2	2	2	0	2
Security	1	1	1	1	1	1	1	1	1	1	1
Spectrum Protection	1	1	2	2	2	1	1	2	1	1	1
Security - Authentication and Integrity	2	2	2	2	1	1	1	2	1	2	2
Security - Robustness to Deliberate Interference	1	1	1	1	1	1	1	1	1	2	1
Transition	1	2	2	0	2	2	2	2	2	0	2

Step 6. Evaluate Technologies vs. AHP Criteria (3)

- Technical metrics were compared against COCR requirements to apply a meets/doesn't meet decision
  - If technology provided a defined capability or met or exceeded performance requirements, a "meets" decision was made (shown by check-mark)

	Function/Service		
	Air/Ground Addressed Data	Air/Air Addressed Data	Ground/Air Broadcast Data
W-CDMA	√		√
APCO P34	√	√	√
Inmarsat SBB	√		√
L-Band E-TDMA	√	√	√
Custom Satellite System (e.g. SDLS)	√		√
LDL	√		√
B-VHF	√	√	√
Link 16	√	√	√

Step 6. Evaluate Technologies vs. AHP Criteria (4)

	Performance			
	Number of Users	Data Rate		QoS
		ATS-only	ATS & AOC	
W-CDMA	Meets in All Domains	√	√	√
APCO P34	Meets in All Domains	√	√	√
Inmarsat SBB	Meets for ATS Traffic Load[1]	√[2]	√[2]	√
Broadband E-TDMA	Meets in All Domains	√		√
Custom Satellite System (e.g. SDLS)	Meets in All Domains	√	√	√
LDL	Meets in TMA and ER Does not meet in APT	√		√
B-VHF	Meets in TMA and ER Does not meet in APT	√	√	√
Link 16	Meets in All Domains	√		√

1. Number of users supported calculated based on requirement that capacity be provided with availability of .99999 or greater; To meet required availability of capacity, an insufficient number of users can be supported when considering combined ATS & AOC traffic load
2. Meets per-user data rate requirements within each domain

Step 6. Evaluate Technologies vs. AHP Criteria (5)

- For institutional criteria, a “meets” decision was associated with green and yellow ratings

	Technical Maturity	Ground Cost	Aircraft Cost	Safety/Security	Transition
W-CDMA	🔴	🔴	🟢	🟡	🟡
APCO P34	🟡	🟡	🟢	🟡	🟢
Inmarsat SBB	🟡	🟡	🟡	🟡	🟢
Broadband E-TDMA	🔴	🟡	🟢	🟡	🟢
Custom Satellite System (e.g. SDLS)	🟡	🔴	🟢	🟡	🔴
LDL	🟡	🟡	🟢	🟡	🟢
B-VHF	🔴	🟡	🟢	🟡	🟢
Link 16	🔴	🔴	🔴	🟡	🔴

Step 6. Evaluate Technologies vs. AHP Criteria (6)

- Individual evaluation criteria results were then rolled into Level-1 decision factor assessments

Technology Family	Cellular
General Solution	WCDMA
Flight Domain	
APT	Yes
TMA	Yes
ENR	Yes
OR	No
P	No
AOA	Yes
Functionality	
A/G & G/A Addressed	Yes
Ground Originated Broadcast	Yes
A/A Addressed	No
Air Originated Broadcast	No
Data Rate (kbps)	
Data Rate for ATS (kbps)	2000
Data Rate for ATS+AOC (kbps)	2000
Max Number Users	600
QoS	Yes
Technical solution maturity	0
Ground infrastructure cost solution	0
Avionics installation cost	2
Security	1
Transition	1

Technology Evaluation Against Evaluation Criteria

Individual evaluation criteria meets/ doesn't meet decisions

Phase II	APT	TMA	ENR	OR	Polar	AOA
Domain	1	1	1	0	0	1
	1	1	1	0	0	0
	1	1	1	0	0	0
		0				
		0				
ATS	1	1	1	1	1	1
ATS_AOC	1	1	1	1	1	1
	1	1	1	1	1	1
	1	1	1	1	1	1

Binary Matrix of Evaluation Criteria Analysis Results

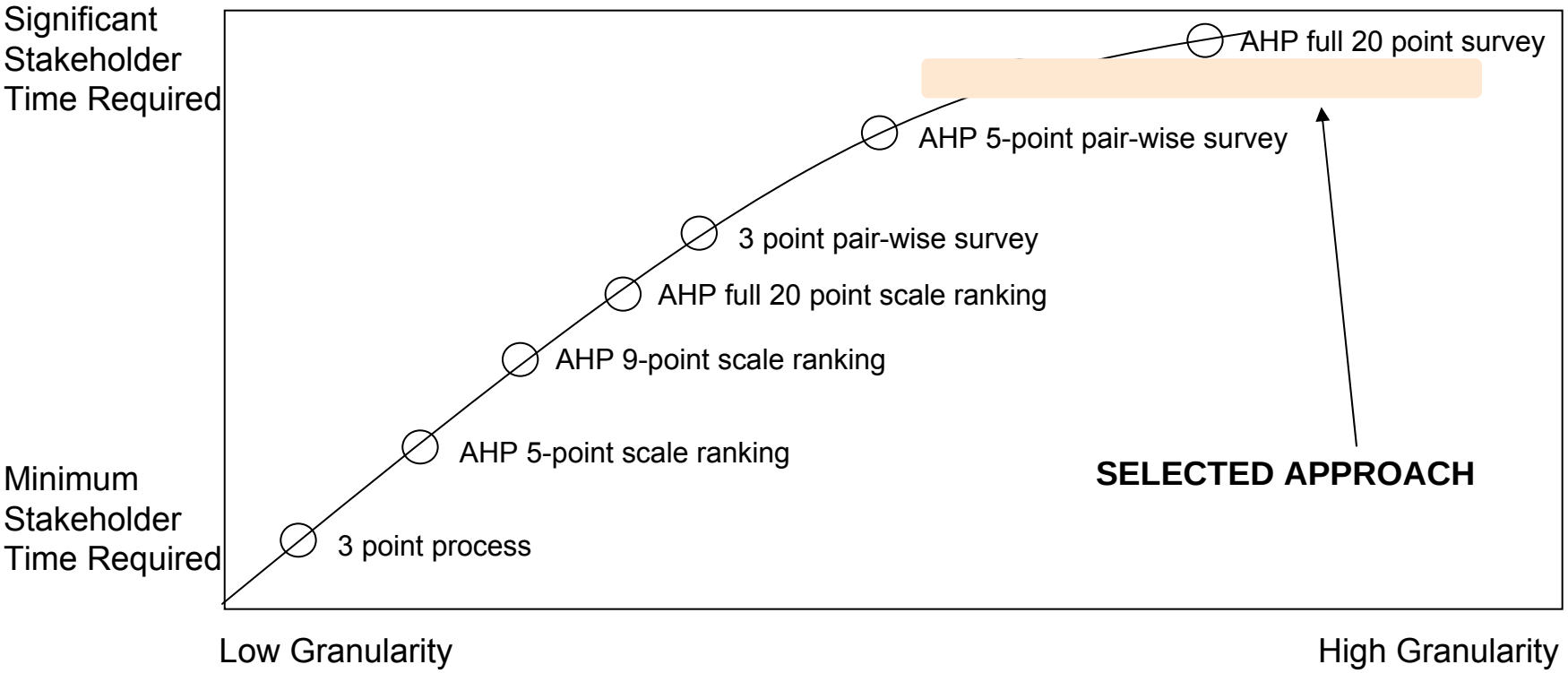
A meets/doesn't meet decision is applied to each Level-1 Decision Factor based on associated evaluation criteria

Meets ATS_G-A-Addressed_COCR Requirements	1
Meets ATS_G-A-Broadcast_COCR Requirements	1
Meets ATS_A-A-Addressed_COCR Requirements	0
Meets ATS_A-A-Broadcast_COCR Requirements	0
Meets ATS&AOC_G-A-Addressed_COCR Requirements	1
Meets ATS&AOC_G-A-Broadcast_COCR Requirements	1
Meets ATS&AOC_A-A-Addressed_COCR Requirements	0
Meets ATS&AOC_A-A-Broadcast_COCR Requirements	0
Provides highly mature technical solution	0
Provides low ground infrastructure cost solution	0
Provides low avionics installation cost solution	1
Provides highly secure solution	1
Provides low-risk/low complexity service provider transition	1

Level-1 Decision Factors and Associated Binary Assessment Results

Step 7. Compare AHP Criteria Pairwise

- Step 7 of the AHP is the pairwise comparison of AHP criteria (i.e. Level-1 decision factors)
- Selected approach for performing the pairwise comparison was a 9-point pair-wise survey



Compare AHP Criteria Pairwise (2)

- A survey was developed and results collected

Pair-Wise Comparison of CTQ Metrics

ID	CTQ Metric A		Relative Magnitude	Relationship Sense	CTQ Metric B
1	Meets ATS_G-A-Broadcast_COCR Requirements	is	O Extremely O Very Strongly O Strongly O Moderately O Equally	O More Important Than O Less Important Than O Important to	Meets ATS_G-A-Addressed_COCR Requirements
2	Meets ATS_A-A-Addressed_COCR Requirements	is	O Extremely O Very Strongly O Strongly O Moderately O Equally	O More Important Than O Less Important Than O Important to	Meets ATS_G-A-Addressed_COCR Requirements
3	Meets ATS&AOC_G-A-Addressed_COCR Requirements	is	O Extremely O Very Strongly O Strongly O Moderately	O More Important Than O Less Important Than O Important to	Meets ATS_G-A-Addressed_COCR Requirements
4	Meets ATS&AOC_G-A-Broadcast_COCR Requirements				
5	Meets ATS&AOC_A-A-Addressed_COCR Requirements				

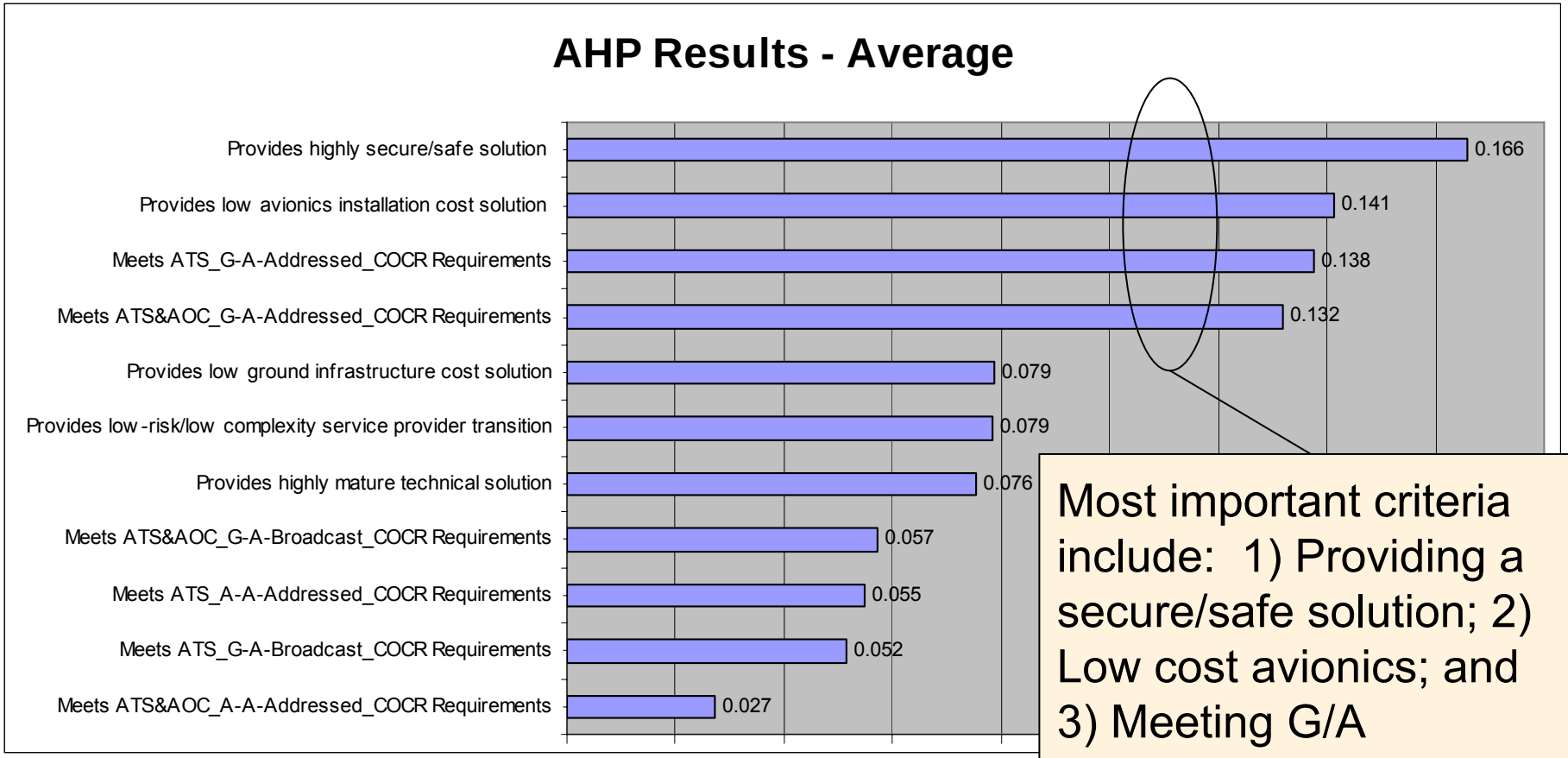
CTQ Ranking Questionnaire

		Question				
5	1	Meets ATS_G-A-Broadcast_COCR Requirements	Is	Equally	Important To	Meets ATS_G-A-Addressed_COCR Requirements
6	2	Meets ATS_A-A-Addressed_COCR Requirements	Is	Equally	Important To	Meets ATS_G-A-Addressed_COCR Requirements
7	3	Meets ATS_A-A-Broadcast_COCR Requirements	Is	Equally	Important To	Meets ATS_G-A-Addressed_COCR Requirements
8	4	Meets ATS&AOC_G-A-Addressed_COCR Requirements	Is	Equally	Important To	Meets ATS_G-A-Addressed_COCR Requirements
9	5	Meets ATS&AOC_G-A-Broadcast_COCR Requirements	Is	Strongly	Less Important Than	Meets ATS_G-A-Addressed_COCR Requirements
10	6	Meets ATS&AOC_A-A-Addressed_COCR Requirements	Is	Strongly	Less Important Than	Meets ATS_G-A-Addressed_COCR Requirements
11	7	Meets ATS&AOC_A-A-Broadcast_COCR Requirements	Is	Strongly	Less Important Than	Meets ATS_G-A-Addressed_COCR Requirements
12	8	Provides highly mature technical solution	Is	Moderatly	Less Important Than	Meets ATS_G-A-Addressed_COCR Requirements
13	9	Provides low ground infrastructure cost solution	Is	Very Strongly	More Important Than	Meets ATS_G-A-Addressed_COCR Requirements
14	10	Provides low avionics installation cost solution	Is	Very Strongly	Less Important Than	Meets ATS_G-A-Addressed_COCR Requirements
15	11	Provides highly secure/safe solution	Is	Extremely Very Strongly Strongly Moderatly Equally	More Important Than	Meets ATS_G-A-Addressed_COCR Requirements
16	12	Provides low-risk/low complexity service provider transition	Is		More Important Than	Meets ATS_G-A-Addressed_COCR Requirements
17	13	Meets ATS_A-A-Addressed_COCR Requirements	Is		Less Important Than	Meets ATS_G-A-Broadcast_COCR Requirements
18	14	Meets ATS_A-A-Broadcast_COCR Requirements	Is		Less Important Than	Meets ATS_G-A-Broadcast_COCR Requirements

Compare AHP Criteria Pairwise (3)

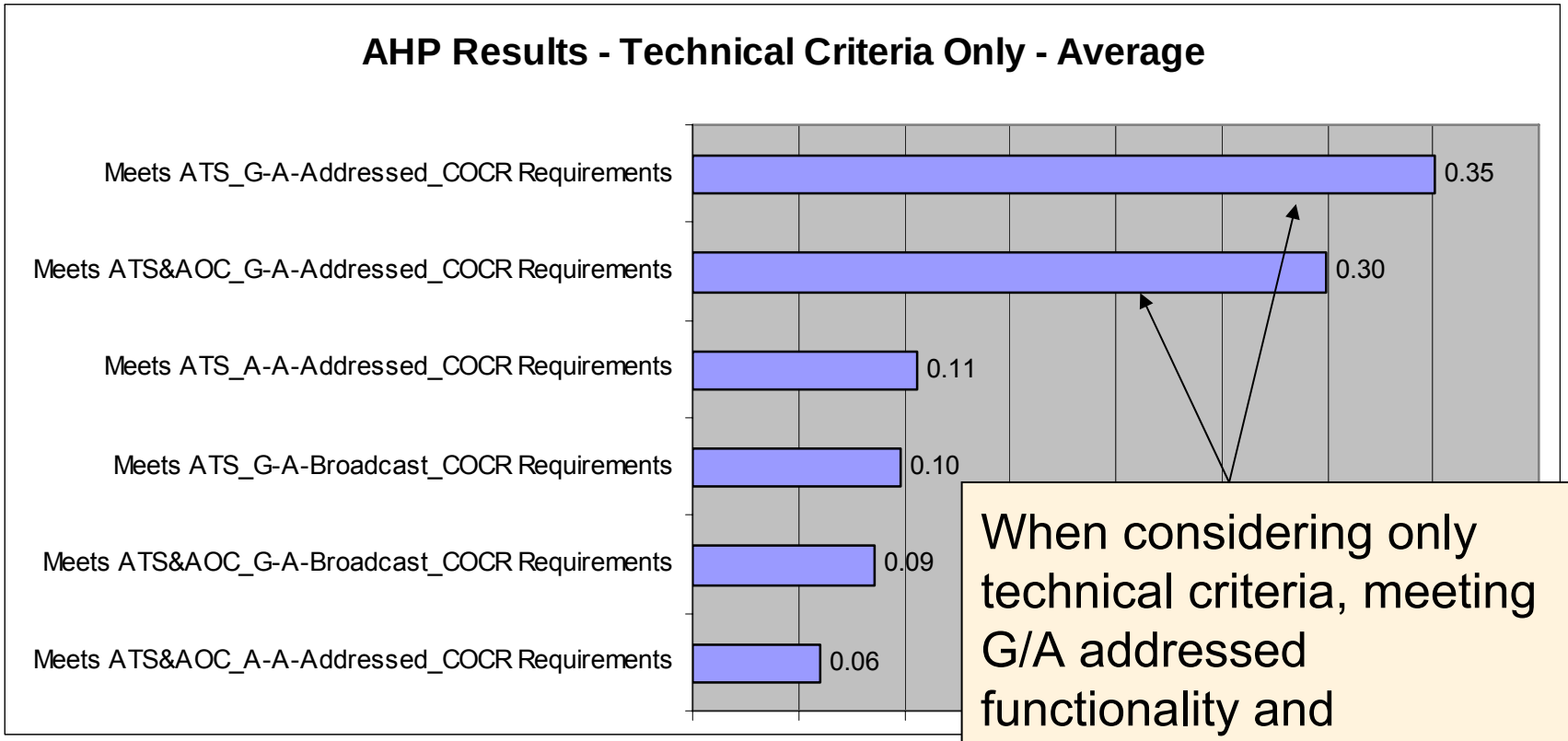
- To synthesize AHP results, a geometric mean calculation was applied to each pair-wise comparison question
  - This resulted in an average response matrix to be used to calculated average AHP Criteria “relative importance” weightings
- Four sets of average results were computed; the first supports the overall technology evaluation process while the others support sensitivity analysis
  - All Decision Factors (overall ranking)
  - Technical Decision Factors only
  - ATS Technical Decision Factors only
  - Institutional Decision Factors only

Overall AHP Criteria Weighting Results



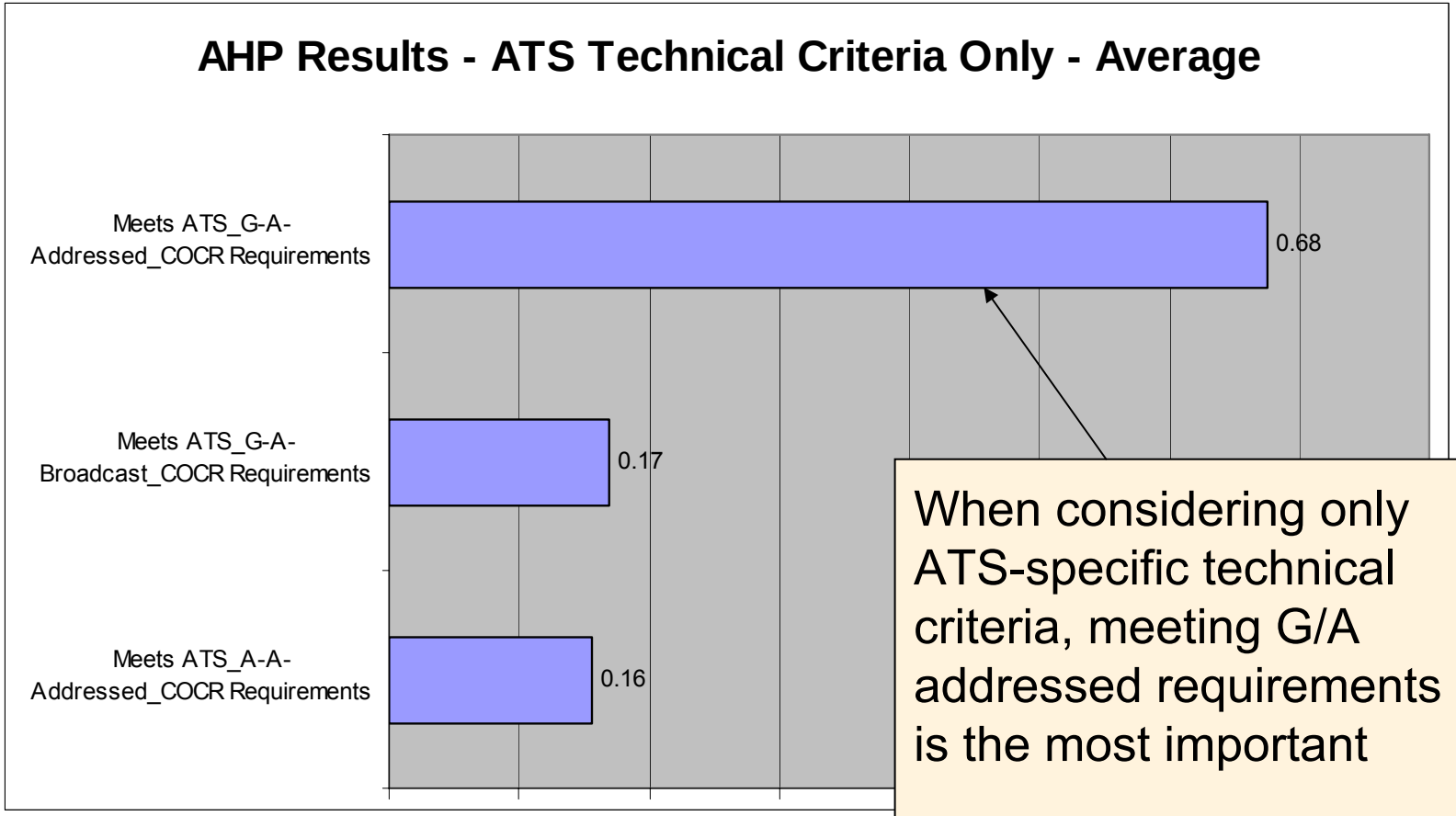
Most important criteria include: 1) Providing a secure/safe solution; 2) Low cost avionics; and 3) Meeting G/A Addressed requirements

Technical Criteria Weighting Results



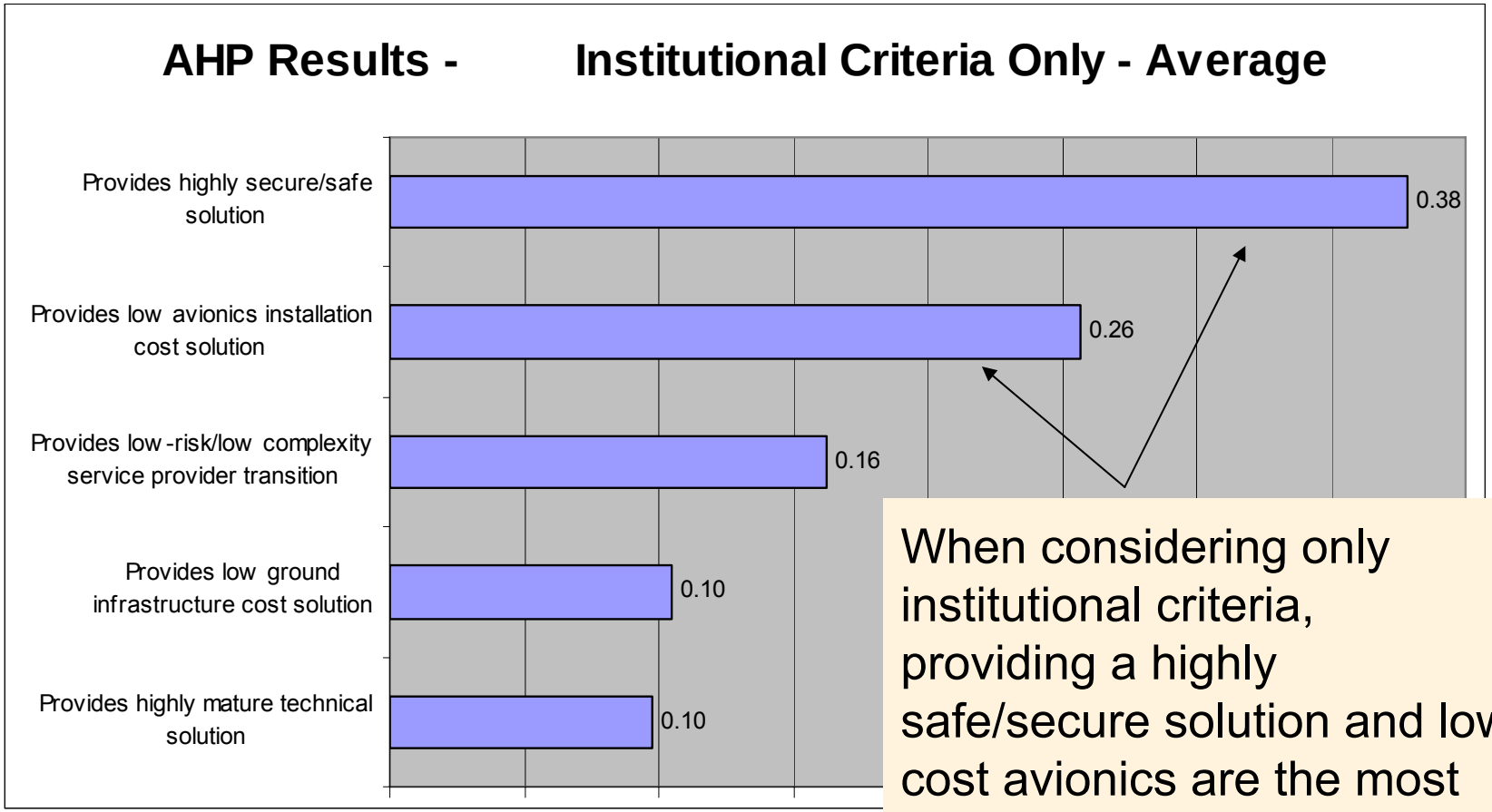
When considering only technical criteria, meeting G/A addressed functionality and performance requirements are the most important

ATS-Only Technical Criteria Weighting Results



When considering only ATS-specific technical criteria, meeting G/A addressed requirements is the most important

Institutional Criteria Weighting Results



When considering only institutional criteria, providing a highly safe/secure solution and low cost avionics are the most important considerations

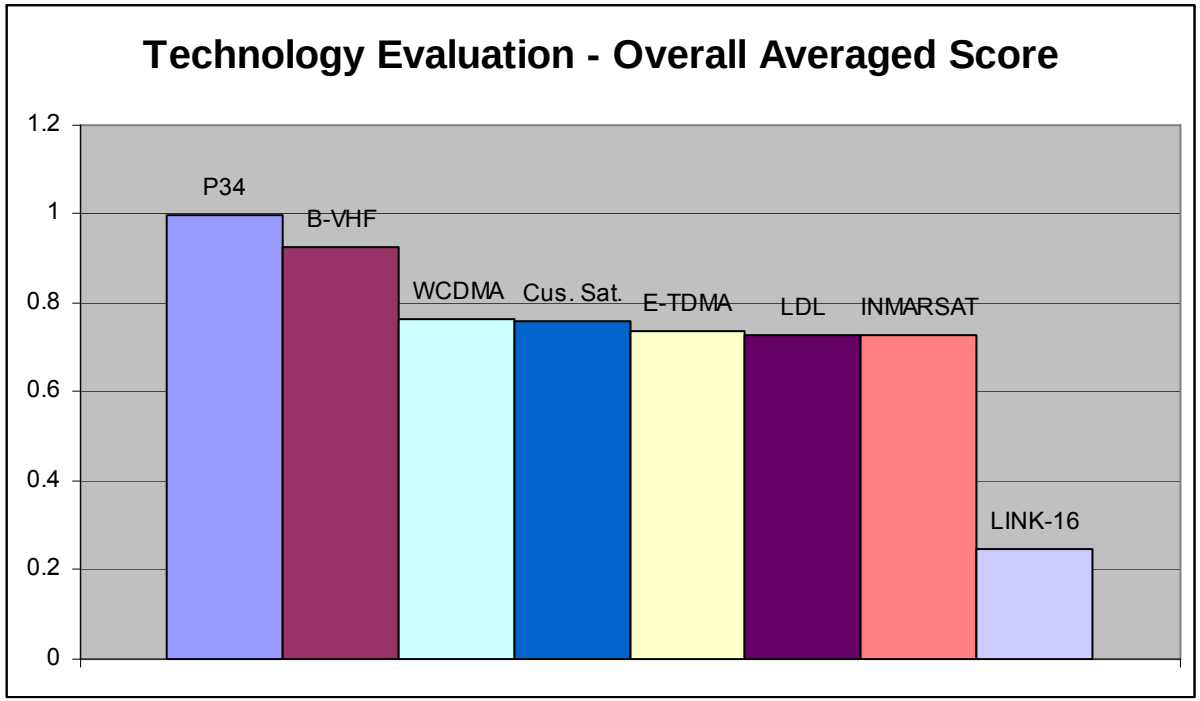
Steps 8/9. Calculate Evaluation Scores & Sensitivity Analysis

- Technology scores were calculated by combining technology assessments against decision factors with calculated decision factor weights

	Technology under Evaluation:	WCDMA		
Selected Ranking Perspective:		CAA		
	Technology CTQ Assessment			
CTQ Measure		Meets	AHP Assessment Value	SCORE
	Meets ATS_AOC_Cont_I COCR Requirements	☑	0.77%	0.007712955
	Meets ATS_Cont_I COCR Requirements	☑	9.51%	0.095103
	Meets ATS_AOC_Cont_II COCR Requirements	☑	0.77%	0.007712955
	Meets ATS_Cont_II COCR Requirements	☑	13.12%	0.131174766
	Meets ATS_AOC_OR_I COCR Requirements	☐	0.77%	
	Meets ATS_OR_I COCR Requirements	☐	8.95%	
	Meets ATS_AOC_OR_II COCR Requirements	☐	0.77%	
	Meets ATS_OR_II COCR Requirements	☐	11.33%	
	Meets ATS_AOC_P_I COCR Requirements	☐	0.77%	
	Meets ATS_P_I COCR Requirements	☐	2.23%	
	Meets ATS_AOC_P_II COCR Requirements	☐	0.77%	
	Meets ATS_P_II COCR Requirements	☐	2.70%	
	Meets ATS_AOC_APT_I COCR Requirements	☑	0.77%	0.007712955
	Meets ATS_APT_I COCR Requirements	☑	4.14%	0.041424168
	Meets ATS_AOC_APT_II COCR Requirements	☑	0.77%	0.007712955
	Meets ATS_APT_II COCR Requirements	☑	5.02%	0.05023024
	Provides highly mature technical solution	☑	3.42%	0.034161924
	Provides low ground infrastructure cost solution	☐	11.01%	
	Provides low avionics installation cost solution	☑	0.81%	0.008095755
	Provides highly secure solution	☑	11.01%	0.110120726
	Provides low-risk/low complexity service provider transitio	☑	10.59%	0.105881585
			TOTAL	0.607043985

Overall Evaluation Score

	All Criteria
W-CDMA	.7638
APCO P34	1
Inmarsat SBB	.7289
Custom Satellite System (e.g. SDLS)	.7608
E-TDMA	.7354
LDL	.7289
B-VHF	.9245
Link 16	.2479

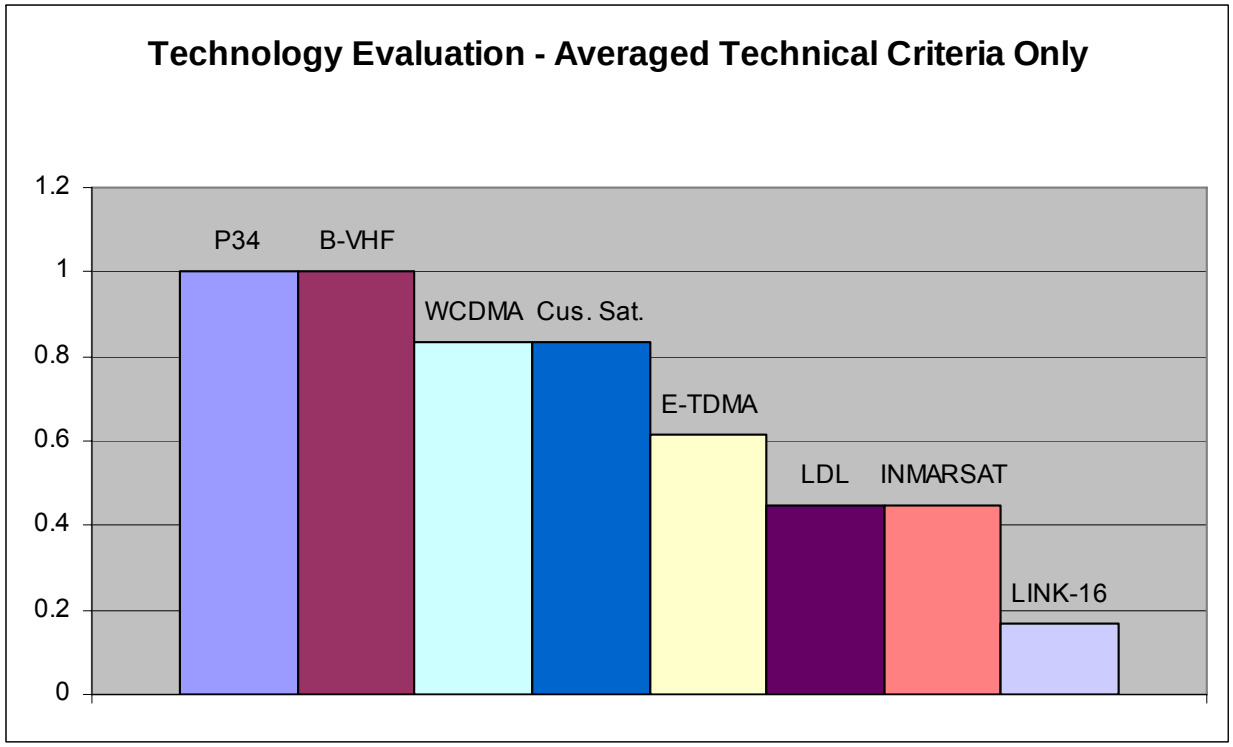


Initial consideration of all results indicates that P34 and B-VHF are the best performers

One technology, Link 16, is a stand-out poor performer

Technical Criteria Scores

	Technical Criteria Only
W-CDMA	.8345
APCO P34	1
Inmarsat SBB	.4495
Custom Satellite System (e.g. SDLS)	.8345
E-TDMA	.6151
LDL	.4495
B-VHF	1
Link 16	.1656

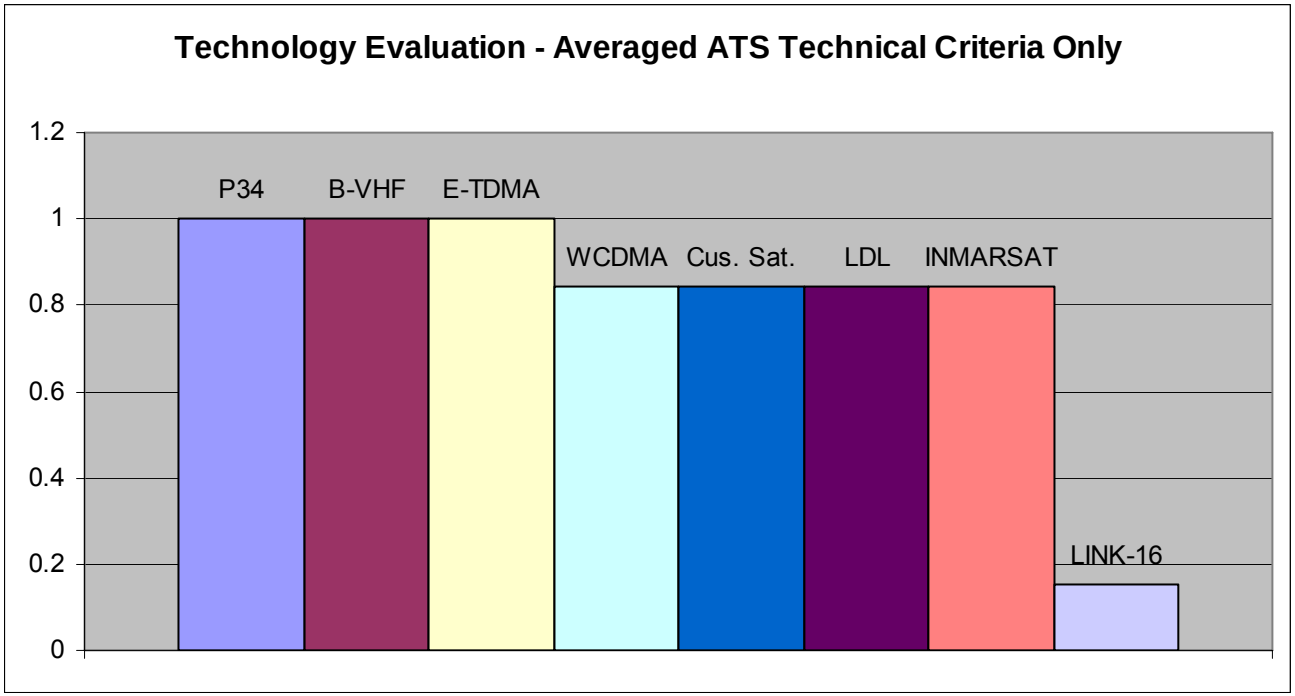


This view of the results can be used as a positive discriminator; several technologies (P34, B-VHF, WCDMA, and Custom Satellite, and E-TDMA), that meet or come close to meeting all technical criteria can be identified

Low performers could be “ruled out”, but first consider ATS only results

Technical Criteria Scores (2)

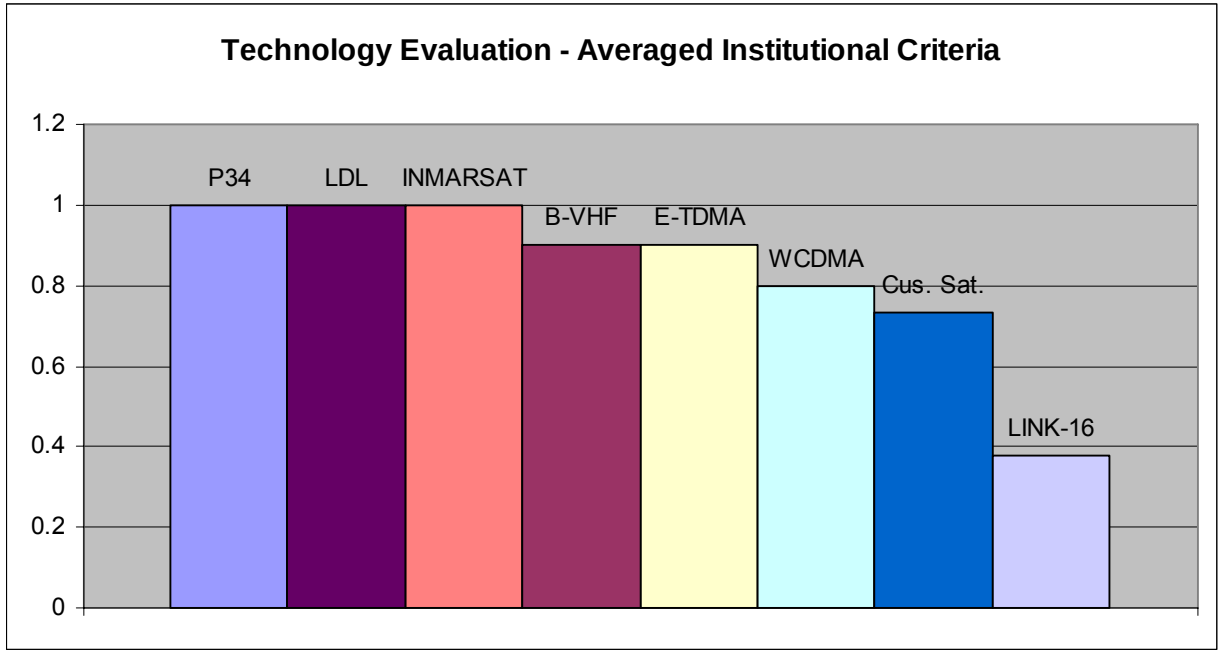
- Within the assessment of technical criteria, a further distinction of meeting ATS-only needs was evaluated
  - Technologies may have applicability if, at a minimum, they meet ATS needs



If it is acceptable to consider solutions for meeting ATS-only requirements, then the only candidate to "rule out" based on technical criteria is Link-16

Institutional Criteria Scores

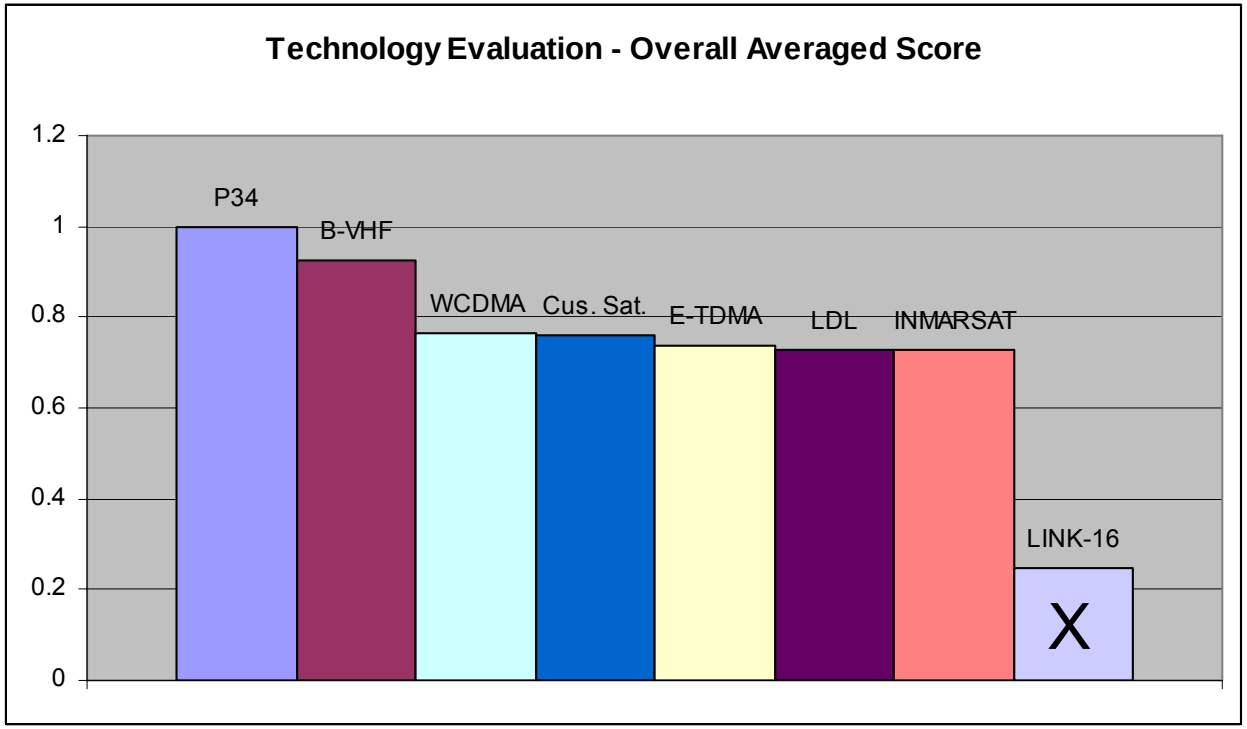
	Institutional Criteria Only
W-CDMA	.7974
APCO P34	1
Inmarsat SBB	1
Custom Satellite System (e.g. SDLS)	.7327
E-TDMA	.9023
LDL	1
B-VHF	.9023
Link 16	.3783



This view of the results can be used as a negative discriminator; most technologies perform very well against institutional criteria; Link-16 is a poor performer, followed by custom satellite and WCDMA (which don't perform poorly, but are slightly behind the rest of the pack)

Results

- Applying observations of sensitivity analysis
  - Link 16 is overall not a strong performer
  - LDL, Inmarsat are not strong performers in meeting ATS & AOC combined technical requirements, but may be satisfactory for an ATS-only system



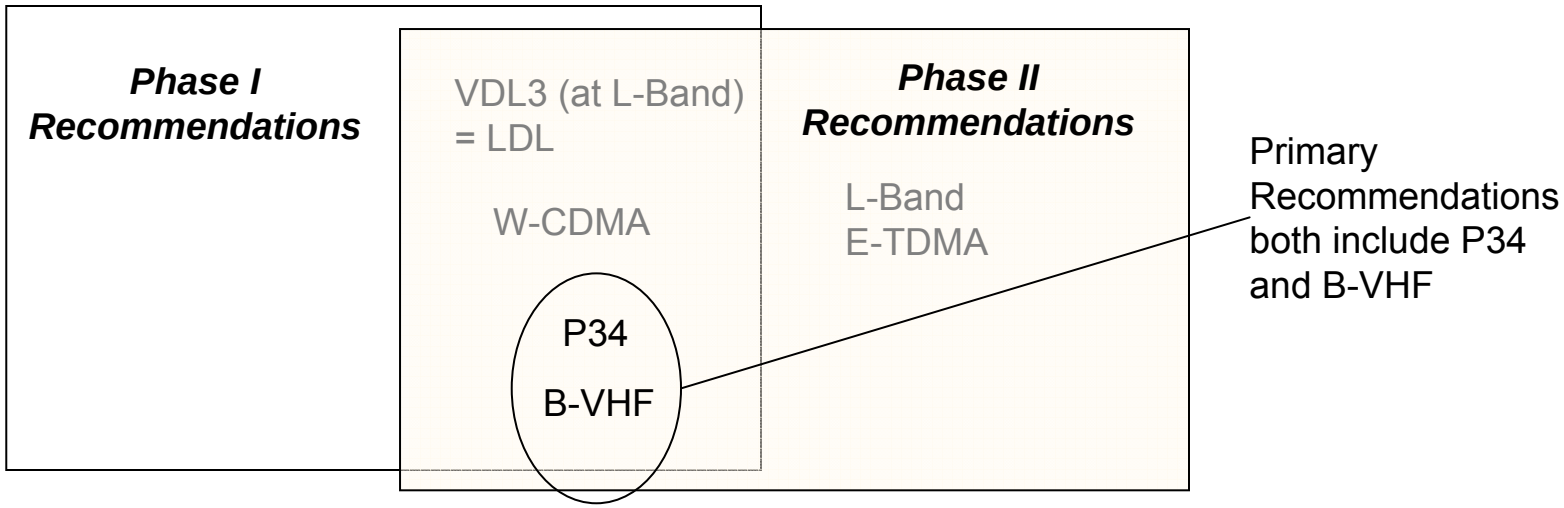
Overview of Best Performers & Comparison to Phase I Results

Best Performers

- Best performers include P34 and B-VHF
  - Second group of capable technologies include W-CDMA, Custom Satellite, E-TDMA, LDL, and Inmarsat
- Detailed study has been performed for LDL, P-34 and Inmarsat during FCS Phase II
  - Results indicated that Inmarsat SBB, as a standalone service, will not meet availability requirements of the COCR
    - As a consequence of these detailed analyses, both Inmarsat and Custom Satellite solutions **are not recommended** at this juncture
  - LDL may require equalization, but outperforms P34 in its ability to not interfere with existing equipment
  - P34 looks to be a good solution technically, but will have to be studied more thoroughly in terms of its potential to interfere with existing systems
- Of the best performers, B-VHF, E-TDMA and W-CDMA need further detailed evaluation

Comparison to Previous Screening Results

- Phase I screening had slightly different focus
  - Consideration was given to both voice and data requirements
    - Current focus is on data capabilities
  - Results and sensitivity analysis identified best all-around technology performers as well as best performers in the data domain
    - Best performers included B-VHF; W-CDMA; P-34 and VDL3
- Comparison of Phase I and Phase II results



Observations

- Initial implementation of the suggested evaluation process (Analytical Hierarchy Process, AHP) identifies two leading candidates, P34 and B-VHF
  - Secondary candidates include W-CDMA, E-TDMA, and LDL
  - 802.16e is recommended for use on the airport surface and terminal area, pending further investigations
  - Inmarsat, Iridium and any emerging satellite technologies that utilize the AMS(R)S spectrum are recommended for remote airspace where terrestrial infrastructure either does not exist or can not be implemented
- Detailed investigations of the following technologies is recommended
  - WCDMA
  - B-VHF
  - L-Band E-TDMA

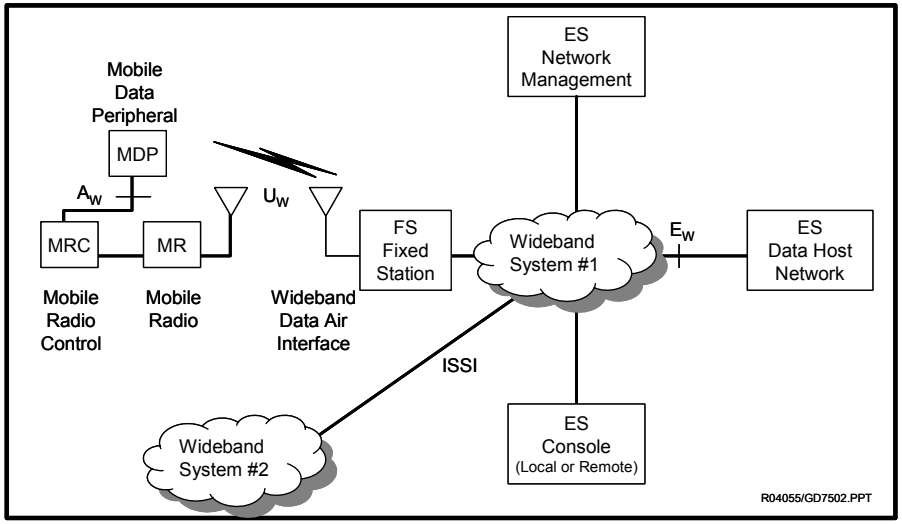
Supplemental – Technology Descriptions

Technologies that Scored Well

- An overview of the best performers is provided on the following slides
  - P34
  - B-VHF
  - W-CDMA
  - L-Band E-TDMA
  - LDL

P34 Description

- Overview provided in a previous briefing
  - APCO Project 34 is a EIA/TIA standardized system for provision of packet data services in an interoperable dispatch oriented topology for public safety service providers
  - Two air interfaces, but IOTA offers higher capacity and is more likely applicable to the FRS
    - Use a form of Multi-Carrier Modulation (OFDM)
  - Scalable adaptable parameters include number of RF subchannels, modulation type and modulation rate
  - Architecture Elements:
    - Mobiles
    - Fixed Ground Stations
    - Network Management
    - End Systems



B-VHF Description

- B-VHF is a development effort for a future aeronautical ATC communications system
  - Currently developed within the FP6 European research project B-VHF ("Broadband VHF Aeronautical Communications System Based on MC-CDMA").
  - The stated goal of the B-VHF project is to verify the feasibility of a broadband VHF aeronautical communications system based on the MC-CDMA technology.
- The B-VHF Project is 50% funded by the European Commission Framework Program for Research and Technological Development.
- In furthering the goals of B-VHF, a B-VHF consortium has been developed.
  - Broad range of stakeholders, including research organizations, an airline, equipment vendors, and an ATM service provider

B-VHF Description (2)

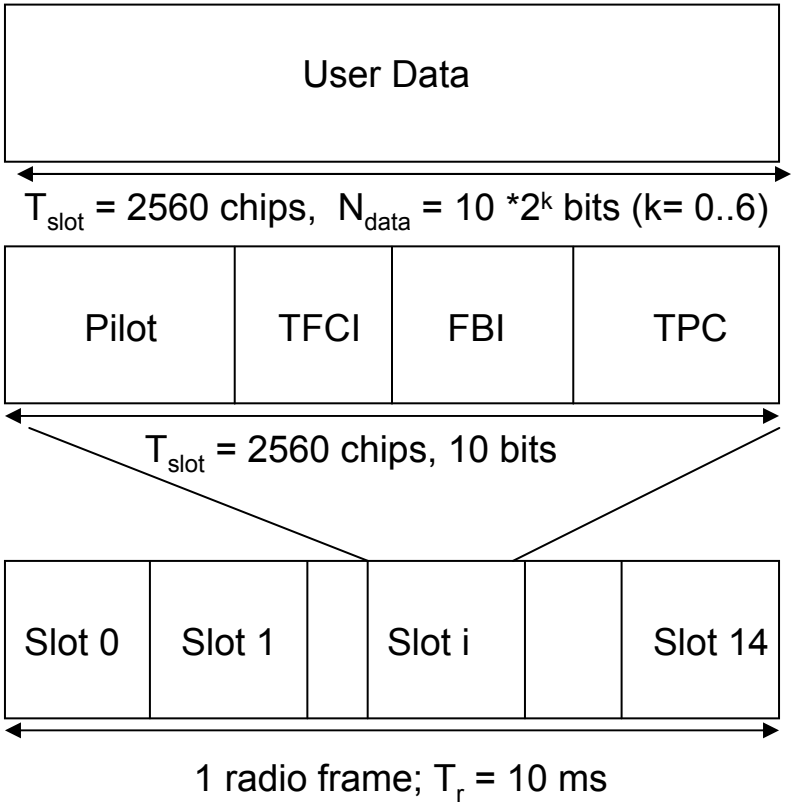
- Stakeholders
  - ATM service provider
    - NATS
  - Airline and aeronautics communication equipment provider
    - Lufthansa and Frequentis
  - Research organizations
    - DLR
    - BAES
    - Scientific Generics
    - Ghent University
    - Polytechnic University Madrid
    - University Salzburg
    - DFS
    - University Las Palmas

B-VHF Description (3)

- The B-VHF project intends to use state-of-the art communications concepts to meet the requirements of ATS and AOC A/G communications
  - MC-CDMA and FDMA for the uplink (aircraft to base station)
    - Spreading codes and other parameters not currently defined
    - Likely choice is L=8
  - OFDMA or MC-CDMA for the downlink (base station to aircraft)
  - Multi-user detection techniques to reduce multi-user interference
  - Reduction of peak-to-average power effects in OFDM by use on non-redundant linear precoding (as is used in Project 34 IOTA air interface)
- Project intends to reuse as much technology as possible from VDL Mode 3, including vocoder, frame structures, and management channel concepts

W-CDMA Description

- W-CDMA is a third generation evolution of the Global System for Mobile Communications (GSM)
- W-CDMA is a direct spread, wideband frequency division duplex CDMA standard developed by 3GPP
  - Uses 5 MHz channel (3.84 Mcps)
  - Data is transmitted in frames (data frames and control frames)
    - Frame length is 10 ms and each frame is divided into 15 slots corresponding the to fast power control period
  - Modulation
    - QPSK modulation is used on the downlink
    - BPSK on the uplink



W-CDMA Description (2)

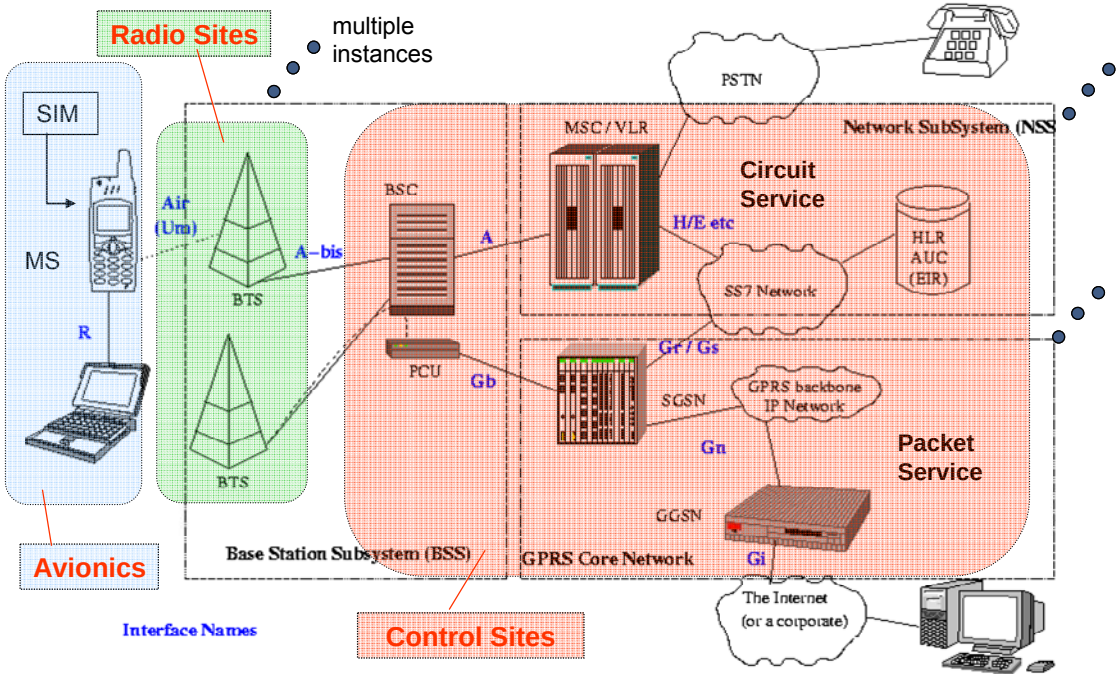
- Scrambling and Spreading codes
  - Both long and short scrambling codes are used
  - Codes are mobile specific in the uplink and ground station specific in the downlink
  - Spreading codes are call Orthogonal Variable Spreading Factor (OVSF) codes
    - Channelization codes (OVSF) are the same in each cell whereas scrambling codes are different among adjacent cells
- Channel spreading codes partition capacity of each transmission slot:
  - High spreading factor creates many partitions (e.g., 128) at low data rate
  - Low spreading factor creates few partitions (e.g., 4) at a high data rate

Slot Format #i	Channel Bit Rate (kbit/s)	Channel Symbol Rate (kbit/s)	SF	Bits/Frame	Bits/Slot	N_{data}
0	15	15	256	150	10	10
1	30	30	128	300	20	20
2	60	60	64	600	40	40
3	120	120	32	1200	80	80
4	240	240	16	2400	160	160
5	480	480	8	4800	320	320
6	960	960	4	9600	640	640

W-CDMA Concept of Use

- Suggest use of circuit service
  - Packet service recommended in Phase I
    - Better suited for voice and data mix, but has TDMA-based bandwidth partitioning (with range limitations, e.g. 40 km)
  - With focus on data only, circuit service for Phase II
- Deployment in DME band (960 – 1024 MHz)

Notional Integration of 3G Elements into Infrastructure



3G suite of elements and interfaces have tentacles that reach far beyond the air interface

L-Band E-TDMA Description

- As introduced previously, this is a data communication concept for aeronautical communications
  - Designed with two modes of operation
    - Ground-supported mode (for aircraft within range of a ground VDL… these stations may or may not be interconnected)
    - Autonomous mode (where aircraft fly without ground VDL infrastructure)
  - Defined to support A/G point-to-point data communications; A/A, A/G and G/A multicast; and A/A point-to-point data communications
- Statistical Self-Synchronization TDMA frame structure in a cellular layout
  - Does not required GPS-synchronization (self-synchronizing)
  - Candidate physical layers include D8PSK, D4PSK and GFSK
  - TDMA frame structure that includes unconditional access to an exclusive primary slot in every frame and reservation-based access to pools of secondary slots
  - Self-insertion rather than cellular handover

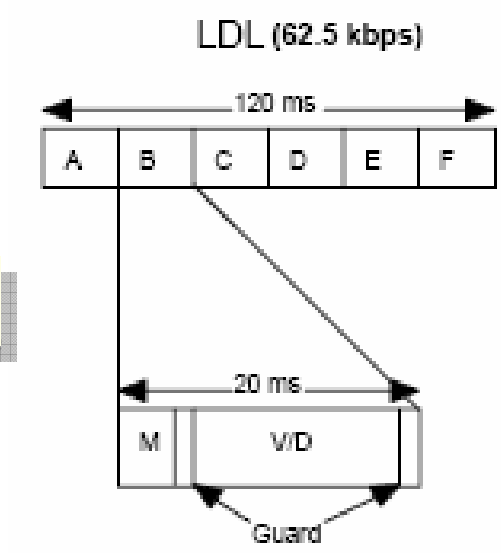
LDL Description

- Band-shifted specification of VDL-3
  - Can provide a data only communication link
  - Upper layers almost identical to VDL3
    - May hasten standardization process
  - Physical layer is similar to Universal Access Transceiver, but with lower data rate

Comparison of VDL3 and LDL Physical Layer Parameters

	VDL Mode 3	LDL
Frequency Band	118 -137 MHz	960 – 1024 MHz
Modulation Type	D8PSK	Binary CPFSK
Bit Rate	31.5 kbps	62.5 kbps *
Eb/No (including losses)	17 dB	11 dB **
Cochannel D/U	20 dB	6 - 9 dB

* To be optimized. Can be anywhere between 37.5 kbps to 100 kbps.
** Noncoherent detection. Could be improved with more complex demodulator

L-Band Digital Link for Air Traffic Services Data Communications, Warren Wilson, May 2, 2006

Proposed LDL Frame Structure