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Research paper

An Integrated Spectrum-Engineering and Safety-Management Framework for VHF Air-Traffic-Service Frequency Migration

The Kolwezi Airport (FZQM) Case Study

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KEYWORDS

aeronautical VHF

designated operational coverage

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ABSTRACT

Background: Regional airport modernization frequently requires new aeronautical VHF assignments while legacy channels, neighboring stations, radio-navigation aids and operational habits remain active. Existing spectrum-planning and safety-management guidance is often applied in separate workstreams. *Objective*: This study develops an integrated, auditable method combining International Civil Aviation Organization (ICAO) frequency planning, International Telecommunication Union (ITU) propagation and electromagnetic-compatibility principles, and safety management of operational change. The method is applied to Kolwezi Airport (FZQM), Democratic Republic of the Congo. *Methods*: Candidate channels were screened against the AFI regional allotment plan, national channel-selection constraints, WGS-84 geodesic distances, designated operational coverage (DOC), ICAO cochannel separation criteria, adjacent-channel precautions, navigation-aid compatibility, third-order intermodulation products, and a safety-managed transition model. *Results*: The preferred candidates are 118.900 MHz for Tower, 120.400 MHz for Approach (APP-I), and 121.700 MHz for Ground. The nearest publicly identified cochannel stations are 307.0, 979.6 and 593.7 NM away, compared with conservative screening minima of 206, 540 and 35 NM, yielding margins of 101.0, 439.6 and 558.7 NM. However, calculated intermodulation products at 116.1, 117.4 and 117.6 MHz fall within the VOR/ILS localizer band, requiring cavity filtering, antenna isolation and radiated testing. *Conclusions*: The three assignments are technically admissible candidates, not final authorizations. Operational use remains conditional on official Frequency Finder/COM List 3 coordination, approved DOC and EIRP, field coverage and CEM tests, AIRAC publication, trained personnel, and an 84-day post-implementation assurance period with a conditional extension to 168 days.

1. Introduction

Aeronautical VHF voice communication remains a safety-critical component of air traffic services (ATS). Although

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digital communication is expanding, controller-pilot radiotelephony continues to support tactical clearances, traffic information, abnormal and emergency coordination, and recovery from degraded modes. The 117.975-137 MHz band is therefore both operationally indispensable and increasingly congested. ICAO frequency planning seeks to protect each assignment within its designated operational coverage while enabling geographically efficient reuse (ICAO, 2022a).

Frequency assignment is a constrained combinatorial problem: a channel must be compatible with the requested service, regional allotment, receiver selectivity, cochannel and adjacent-channel separations, terrain, transmitter characteristics, and existing assignments. General frequency-assignment research frames the problem as an interference-constrained graph or optimization problem (Aardal et al., 2002, 2007), while recent aviation-specific work has explored multi-objective optimization for navigation-station assignments (Hao et al., 2025). However, an apparently feasible assignment can still fail operationally because of local propagation, co-sited intermodulation, incomplete aeronautical information, human habit, or inadequately managed transition.

Airport and air-ground propagation studies show that buildings, terrain, antenna geometry and multipath can produce location-specific deviations that cannot be resolved by nominal distance alone (Suga et al., 2020). Studies of aeronautical electromagnetic interference also demonstrate the practical relevance of third-order intermodulation and the need for filtering and measurement (Acakpovi et al., 2019; Sitopu and Cahyadi, 2022). In parallel, ATM safety research emphasizes that technical changes alter work-as-done, interfaces and recovery strategies; they therefore require structured preliminary and system safety assessment rather than simple equipment reconfiguration (Patriarca et al., 2016; Woltjer et al., 2015).

This paper addresses that integration gap through a case study at Kolwezi Airport (FZQM), where the existing Tower frequency 118.300 MHz is to be replaced by 118.900 MHz, while new frequencies are proposed for Approach (120.400 MHz) and Ground (121.700 MHz). The study combines spectrum engineering and safety management into a single evidence chain. Its principal contribution is not a universal optimization algorithm, but a transparent decision framework that can be replicated by air navigation service providers (ANSPs) at regional airports with incomplete measurement data and cross-border coordination requirements.

1.2 Research questions

RQ1: Do the proposed frequencies belong to the correct AFI service allotments and satisfy conservative cochannel separation criteria?
RQ2: What additional constraints arise from DOC geometry, EIRP, radio-navigation aids and co-sited intermodulation?
RQ3: How should the migration from 118.300 to 118.900 MHz be governed so that legacy calls, equipment failure and inconsistent information remain recoverable?
RQ4: Which elements of the method are generalizable to other regional airports, and which require site-specific validation?

1.3 Original contribution

The study proposes an integrated admissibility set, a normalized separation index, a combined spectrum-and-safety workflow, and a risk-based transition assurance period. These are used to transform regulatory requirements into a traceable engineering argument that links candidate selection to implementation evidence.

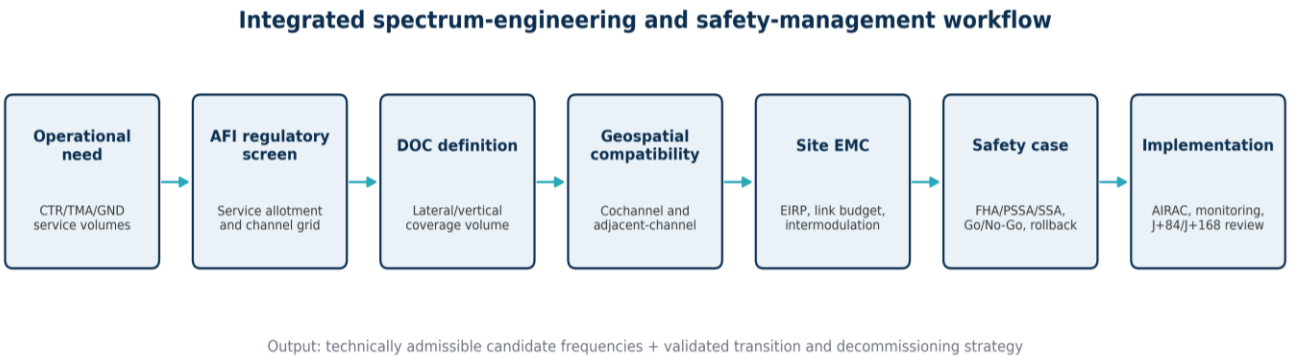

Fig. 1 Integrated workflow linking operational need, spectrum engineering, site EMC, safety assessment and implementation assurance

2. Regulatory and scientific background

2.1 Aeronautical VHF planning in the AFI region

ICAO Doc 9718, Volume II, provides frequency-assignment planning criteria that supplement Annex 10, especially Volume V. The relevant communication band extends from 117.975 to 137 MHz. The AFI regional allotment tables are based principally on 25 kHz channelization, while the national operational context considered here does not yet use intermediate 25 kHz channels. Consequently, the case study uses a 100 kHz subset—118.900, 120.400 and 121.700 MHz—while retaining compatibility with the AFI allotment categories (ICAO, 2017, 2022a).

The candidate set can be represented as the intersection of regulatory, technical and operational constraints:

$$\mathcal{F}^{*} = \mathcal{F}_{\mathrm{AFI}} \cap \mathcal{F}_{\mathrm{grid}} \cap \mathcal{F}_{\mathrm{co}} \cap \mathcal{F}_{\mathrm{adj}} \cap \mathcal{F}_{\mathrm{EMC}} \cap \mathcal{F}_{\mathrm{ops}} \quad (1)$$

Admissible frequency set. AFI = regional allotment; grid = nationally selectable channel subset; co/adj = cochannel and adjacent-channel compatibility; EMC = site compatibility; ops = operational suitability.

2.2 Designated operational coverage

DOC is the combination of designated operational range and designated operational height. ICAO planning protects a service against harmful interference within the State-declared DOC, not indefinitely beyond it. Standard uniform planning values include 25 NM/4,000 ft AGL for TWR, 50 NM/12,000 ft for APP-L, 75 NM/25,000 ft for APP-I and 150 NM/45,000 ft for APP-U. Non-uniform or reduced DOCs may be declared when operationally justified, which is important for spectrum efficiency and cross-border coordination (ICAO, 2022a).

Service category	Uniform range	Uniform height	Case-study use
TWR	25 NM	4,000 ft AGL	Conservative Tower screening volume
APP-L	50 NM	12,000 ft	Horizontally close to the TMA, but vertically restrictive
APP-I	75 NM	25,000 ft	Selected category; actual TMA polygon to be declared
APP-U	150 NM	45,000 ft	Not required for the current design
AS/GND	Aerodrome surface	Local surface volume	Power and antenna height must limit airborne coverage

2.3 Frequency assignment and interference constraints

General frequency-assignment models seek to assign channels while minimizing conflicts, bandwidth use or cost (Aardal et al., 2002, 2007). Aviation assignments add service-volume and safety constraints: a conflict is not only a frequency difference but a function of DOC overlap, antenna height, EIRP, propagation, receiver discrimination and operational consequence. The present work therefore adopts a deterministic regulatory screen followed by site validation, rather than treating spatial distance as a complete interference model.

2.4 Safety management of ATM change

ICAO Annex 19 and Doc 9859 require a systematic approach to hazard identification, risk mitigation, performance monitoring, management of change, training and safety communication. EUROCONTROL SAM provides a complementary engineering structure through functional hazard assessment (FHA), preliminary system safety assessment (PSSA) and system safety assessment (SSA). For voice communications, EUROCONTROL identifies call-sign confusion, undetected simultaneous transmissions, radio interference, non-standard phraseology and prolonged communication loss as recurrent hazards (EUROCONTROL, 2006a, 2006b).

3. Materials and methods

3.1 Case-study system and data sources

The system boundary includes FZQM Tower, the proposed Approach and Ground positions, radio transmitters and receivers, antennas, VCCS, recording and power systems, AIS products, neighboring ATS units and aircraft

operators. The source engineering study used WGS-84 coordinates, public and operationally available frequency records, ICAO/ITU planning criteria and a transition plan. The critical limitation is that a complete official COM List 3 export, measured EIRP, detailed antenna patterns and comprehensive flight-inspection data were not available at the preliminary stage. Public frequency records are therefore treated as screening inputs, not authoritative assignments.

Proposed function	Frequency	AFI class	Initial DOC assumption
Kolwezi Tower	118.900 MHz	TWR	25 NM / 4,000 ft AGL
Kolwezi Approach	120.400 MHz	APP-I	Actual TMA polygon, approximately 51 NM; vertical limit subject to final design
Kolwezi Ground	121.700 MHz	AS/GND	Movement area and aerodrome surface
Legacy Tower	118.300 MHz	Transition fallback	Normal use ends at T0; monitored fallback through J+84, conditionally J+168

3.2 Geodesic distance computation

Station-to-station distances were computed on the WGS-84 ellipsoid. For analytical transparency, the spherical haversine form is shown below, while the numerical results in the project study used geodesic coordinates and were rounded to 0.1 NM:

$$d = 2R\arcsin\left(\sqrt{\sin^2\frac{\Delta\varphi}{2} + \cos\varphi_1\cos\varphi_2\sin^2\frac{\Delta\lambda}{2}}\right) \quad (2)$$

Here, φ is latitude, λ is longitude and R is the reference Earth radius. Final coordination should retain the WGS-84 geodesic solution.

3.3 Conversion of edge-to-edge DOC separation

ICAO Table 2-8 expresses cochannel separation between the nearest edges of the protected DOCs. For two circular uniform DOCs, a conservative station-to-station screening distance is:

$$D_{\min,ij} = R_i + D_{\text{edge},ij} + R_j \quad (3)$$

Ri and Rj are DOC radii; Dedge,ij is the ICAO minimum edge-to-edge separation.

Combination	Edge separation	Site-to-site calculation	Minimum
TWR-TWR	156 NM	25 + 156 + 25	206 NM
TWR-APP-L	212 NM	25 + 212 + 50	287 NM
APP-L-APP-L	268 NM	50 + 268 + 50	368 NM
APP-I-APP-I	390 NM	75 + 390 + 75	540 NM
APP-U-APP-U	520 NM	150 + 520 + 150	820 NM
AS-AS	Specific surface rule	—	35 NM

3.4 Proposed separation indicators

To compare services with very different protected volumes, the study introduces a normalized separation index (NSI) and an absolute margin M. These indicators are not ICAO standards; they are reporting metrics. NSI > 1 indicates that the nearest identified cochannel station lies beyond the conservative screening minimum.

$$\text{NSI}_{ij} = \frac{D_{\text{actual},ij}}{D_{\min,ij}}, \qquad M_{ij} = D_{\text{actual},ij} - D_{\min,ij} \quad (4)$$

NSI is dimensionless; M is expressed in nautical miles.

3.5 EIRP, link budget and propagation validation

Distance screening does not demonstrate coverage. The declared DOC must be supported by transmitter power, feeder losses, antenna gain and geometry. Equivalent isotropically radiated power is calculated as:

$$\text{EIRP}_{\text{dBW}} = P_{\text{TX, dBW}} - L_{\text{feed}} - L_{\text{filter}} + G_{\text{ant, dBi}} \quad (5)$$

Loss terms include feeder, connectors, filters, combiners and other insertion losses.

A first-order link budget can be expressed as Eq. (6), but final aeronautical prediction should use ITU-R P.528-5 and terrain/site data rather than free-space loss alone (ITU-R, 2021).

$$P_R = \mathrm{EIRP} + G_R - L_{\mathrm{prop}} - L_{\mathrm{misc}}, \quad L_{\mathrm{FS}} = 32.44 + 20\log_{10} f_{\mathrm{MHz}} + 20\log_{10} d_{\mathrm{km}} \tag{6}$$

Pr is received power in dBW or dBm; G_R is receiver-antenna gain; Lprop should be obtained from an aeronautical propagation model and validated by measurement.

3.6 Adjacent-channel and site EMC analysis

ICAO planning generally treats first-adjacent interference as localized and transient for equal channel widths, but recommends implementation precautions between ground transmitters and receivers and discourages adjacent assignments at the same site. Co-sited transmitters require a separate EMC analysis because regional frequency planning does not eliminate intermodulation, receiver blocking or passive nonlinear junction effects (ICAO, 2022a). ITU-R SM.329-13 defines harmonic, parasitic, intermodulation and conversion products and measurement methods, while ITU-R SM.1535 addresses protection of safety services from unwanted emissions (ITU-R, 2001, 2024).

$$f_{\mathrm{IM3}} \in \{2f_1 - f_2,\ 2f_2 - f_1,\ f_1 + f_2 - f_3\} \tag{7}$$

Representative third-order intermodulation products. For three carriers, mixed products such as f1 + f2 - f3 must also be evaluated.

3.7 Safety and transition assessment

The transition is treated as an ATM functional-system change. Hazards include continued calls on 118.300 MHz, incorrect transfers, inconsistent AIS data, simultaneous use of old and new Tower channels, insufficient coverage, equipment failure, common-cause failure, intermodulation, incomplete training and delayed rollback. A local risk score may be used for prioritization, while the post-implementation legacy-use ratio provides an objective trend indicator:

$$R_h = S_h \times L_h, \qquad \rho_{\mathrm{old}}(t) = 100\,\frac{N_{118.300}(t)}{N_{\mathrm{mov}}(t)} \tag{8}$$

S and L denote locally defined severity and likelihood. The authority should define the acceptable threshold for the legacy-use ratio ρold(t).

Availability should be monitored for the primary and standby chains. The independent-parallel expression in Eq. (9) is optimistic if both channels share antennas, VCCS, power or remote-control links; a common-cause analysis is therefore mandatory.

$$A = \frac{\mathrm{MTBF}}{\mathrm{MTBF} + \mathrm{MTTR}}, \qquad A_{\parallel} = 1 - (1 - A_1)(1 - A_2) \tag{9}$$

MTBF = mean time between failures; MTTR = mean time to repair. Independence must be demonstrated before using the parallel formula.

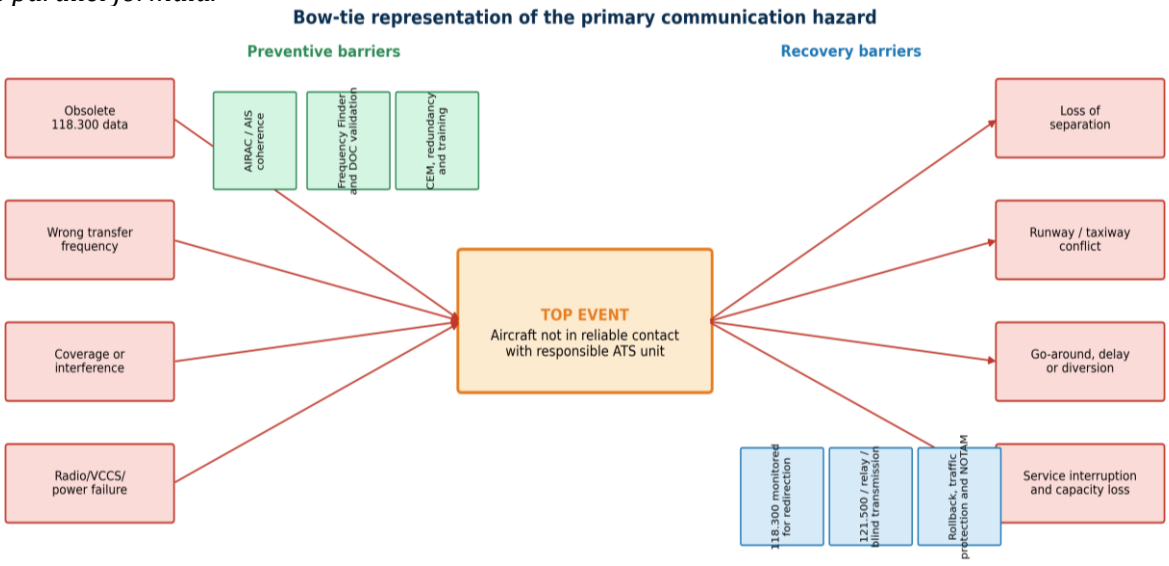

Fig. 2 Bow-tie representation of the principal communication hazard and the required preventive and recovery barriers

3.8 Decision rule and limitations

A candidate is retained only if it passes the AFI service allotment, channel-selectability, cochannel screen, adjacent-channel check, preliminary NAV/COM compatibility, and operational-safety review. The study does not substitute for official frequency coordination, spectrum licensing, equipment certification, antenna siting, flight inspection, or the overall TMA safety assessment. Where inputs are incomplete, the method either uses a conservative assumption or converts the missing value into a pre-implementation evidence requirement.

4. Results

4.1 Regulatory screening

The AFI allotment table identifies 118.900 MHz as a TWR channel, 120.400 MHz within an APP-I block, and 121.700 MHz within the aerodrome surface communication block. The previously considered 126.300 MHz was rejected because it is designated FIS-U (GPS), not APP, in the AFI table. Selection on the 100 kHz subset avoids dependence on intermediate channels while remaining within the regional 25 kHz planning structure.

4.2 Regional station environment

Station	Distance from FZQM	Relevant COM assignments	NAV aids / note
Fungurume FZQF	50.5 NM	118.700 A/G/TWR	Very close; excludes 118.700 reuse
Solwezi FLSW	98.2 NM	118.300 TWR; 123.920 APP	NDB SW 415 kHz
Kamina FZSA	127.7 NM	118.300 TWR; APP data divergent	VOR KMB 114.700
Lubumbashi FZQA	129.2 NM	118.100 TWR; 126.700 APP; 128.100 ACC; 121.900 GND	VOR/DME 116.700; ILS/LOC 109.900
Ndola FLSK	220.5 NM	120.000 APP; multiple TWR channels	VORs 114.000 and 112.100
Saurimo FNSA	307.0 NM	118.900 INFO/AFIS	Nearest decisive public cochannel for Tower

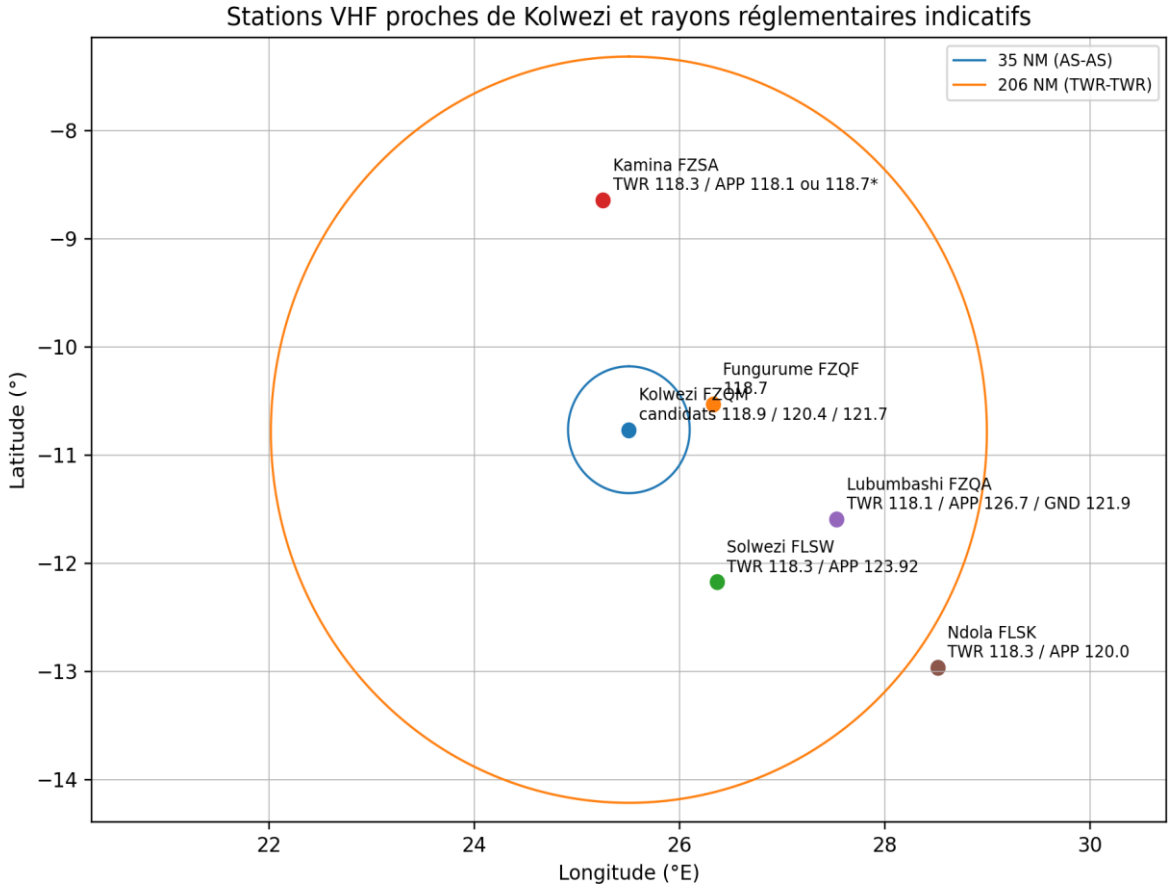

Fig. 3 Regional VHF stations around Kolwezi. The 206 NM ring is the conservative TWR-TWR site-separation screen. Source: authors' WGS-84 calculations based on the project inventory

4.3 Cofrequency screening

Proposed service	Nearest identified cochannel	Actual distance (NM)	Screening minimum (NM)	Margin (NM)	NSI
TWR 118.900	Saurimo FNSA	307.0	206	+101.0	1.49
APP-I 120.400	Malindi HKML	979.6	540	+439.6	1.81
AS/GND 121.700	Kigali HRYR	593.7	35	+558.7	16.96

All three candidates have NSI > 1. The Tower result is the least over-separated and therefore the most sensitive to unrecorded assignments or larger-than-assumed DOC/EIRP. The Ground result has a very large geographical margin, but local surface coverage and on-site blocking remain more relevant than regional reuse distance.

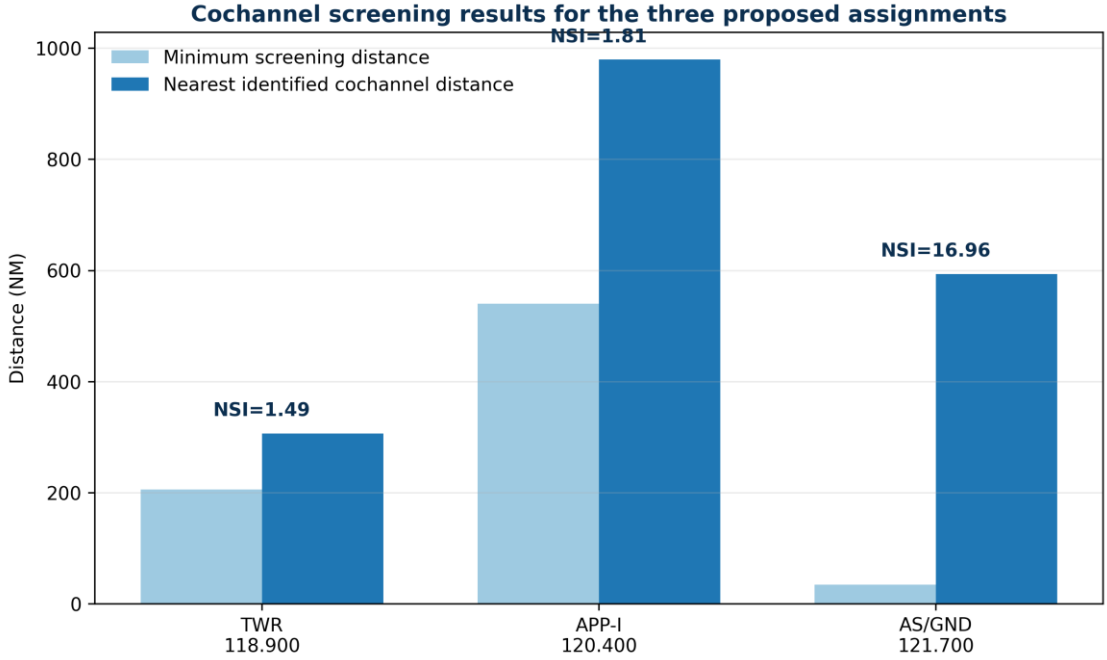

Fig. 4 Conservative cochannel screening distances, nearest publicly identified cochannel distances, and normalized separation indices

4.4 Navigation-aid compatibility and intermodulation

No direct cofrequency exists between the proposed COM channels and the inventoried VOR/ILS localizer channels in the 108-117.975 MHz band. Nevertheless, third-order products created by co-sited non-linearities include 116.1, 117.4 and 117.6 MHz, all within the NAV band. Additional products occur at 119.1, 120.2, 121.9, 123.0, 123.2 and 124.5 MHz in the COM band. Therefore, geographic admission alone is insufficient.

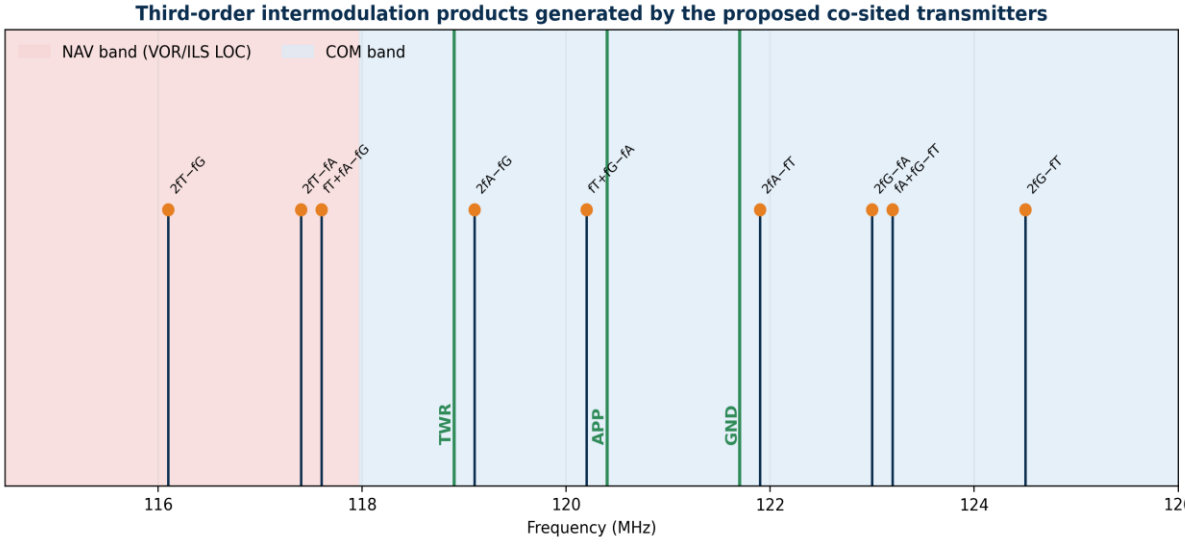

Fig. 5 Calculated third-order intermodulation products. Products within the NAV band require explicit measurement and filtering before commissioning

Product expression	Frequency	Potential impact
2 x 118.900 - 121.700	116.100 MHz	VOR band
2 x 118.900 - 120.400	117.400 MHz	VOR/ILS localizer band
118.900 + 120.400 - 121.700	117.600 MHz	VOR/ILS localizer band
2 x 120.400 - 118.900	121.900 MHz	COM; coincides with a published Lubumbashi GND value
Other third-order products	119.100-124.500 MHz	COM receiver blocking or false squelch opening

4.5 Safety-managed transition architecture

At T0 on Day J, 118.900 MHz becomes the only normal Tower channel. The legacy 118.300 MHz is retained for monitoring, redirection and formal contingency for three AIRAC cycles (84 days). A formal review at J+84 either authorizes decommissioning or, if residual risks remain, a conditional extension to J+168. Permanent simulcast is not recommended because it can mask blocked transmissions, create ambiguous readbacks and undermine a single operational baseline.

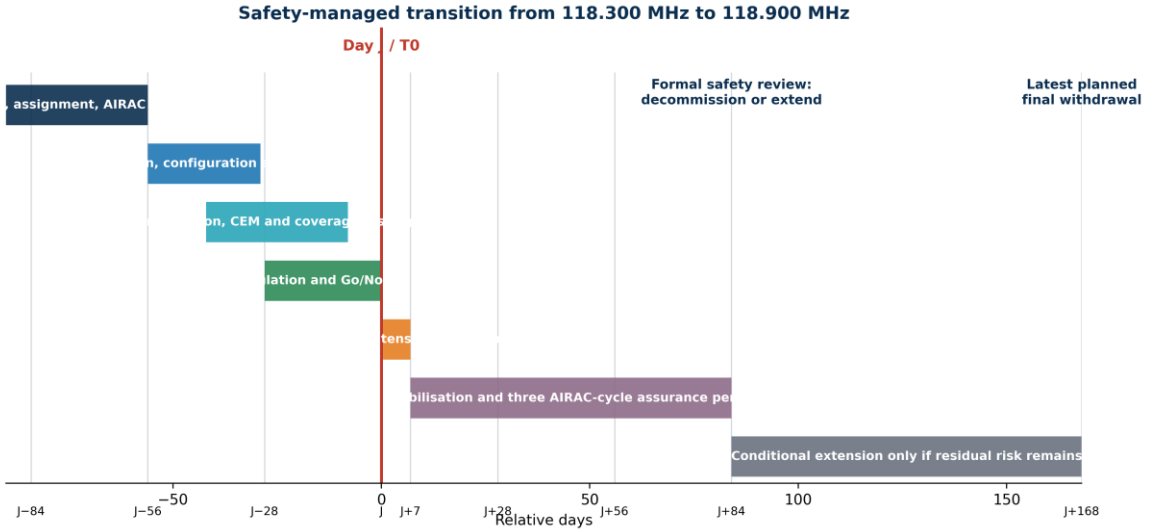

Fig. 6 Transition timeline from assignment and publication to post-implementation review and final withdrawal

Decision point	Required evidence	Decision
J-7 Go/No-Go	Official assignment; AIRAC/NOTAM coherence; successful coverage/CEM tests; trained staff; rollback exercised	Proceed or postpone T0
T0	Primary and standby operational; recording and power verified; low traffic; no uncontrolled emergency	Activate 118.900 and transfer aircraft individually
J+84	Availability and coverage stable; interference closed; legacy calls residual; operators and databases updated	Decommission or justify extension
J+168 maximum	Residual risks closed or accepted; independent standby available; spectrum and AIS withdrawal coordinated	Final withdrawal of 118.300

5. Discussion

5.1 Engineering interpretation

The results support the three-channel solution as a coherent service separation: Tower, Approach and Ground use distinct AFI service categories and are separated by 1.3-2.8 MHz at the site. Regional cochannel margins are positive, but the Tower candidate has a comparatively modest NSI of 1.49. This reinforces the requirement to verify COM List 3, actual DOC, antenna height and EIRP before final coordination. A change in site, power or antenna pattern can enlarge the interfering service volume even when the nominal frequency is unchanged.
The APP-I classification illustrates the distinction between category and actual DOC. A 51 NM lateral TMA is close to APP-L horizontally, yet a vertical requirement above 12,000 ft supports APP-I. The assignment should not automatically protect a 75 NM circle to 25,000 ft; the actual polygon and height should be entered in Frequency Finder. This reduces spectrum sterilization and produces a more defensible cross-border analysis.

5.2 Vertical-design sensitivity: FL145 versus FL245

The source engineering report treated FL245 as a provisional upper work limit. A regional operational architecture may instead define a lower terminal layer to FL145 and allocate the FL145-FL245 layer to an

upper TMA part or the ACC. Both scenarios remain compatible with APP-I because FL145 already exceeds the 12,000 ft uniform APP-L height. The engineering consequence is not a change of channel class, but a change in declared DOC, coverage-test altitudes, coordination responsibilities and cochannel geometry. The article therefore recommends a two-scenario Frequency Finder study before approval.

Scenario	Approach responsibility	DOC implication	Operational consequence
A: TMA Part 1 to FL145	Kolwezi APP below FL145; ACC/upper sector above	Approximately 51 NM polygon to FL145	Smaller protected volume; earlier APP/ACC transfer
B: APP to FL245	Kolwezi APP controls terminal flows to FL245	Approximately 51 NM polygon to FL245	Larger protected volume; stronger coverage and coordination burden

5.3 EIRP and coverage evidence

The study deliberately avoids inventing EIRP values because transmitter power, feeder length, filter insertion loss and antenna gain were unavailable. For doctoral-level technical validation, the final study should report measured transmitter output, insertion losses, antenna gain/pattern, EIRP, receiver sensitivity, required signal-to-noise or signal-to-interference ratio, and the P.528 field-strength prediction at representative altitudes and ranges. Coverage acceptance should be based on sector-by-sector flight or cooperative measurements, not on radio-horizon calculations alone.

5.4 Electromagnetic compatibility and common-cause risk

The intermodulation results are one of the most important findings. They show that well-separated operational channels can produce unwanted energy in safety-critical NAV bands when amplifiers, connectors, antennas or passive structures behave non-linearly. The appropriate response is not simply to change frequencies, because alternative combinations can create different products. Instead, the site requires cavity or band-pass filters, antenna isolation, high-quality connectors, grounding and simultaneous-transmission stress tests. The same common-cause logic applies to redundancy: two radios sharing one antenna, feeder, VCCS or power source do not constitute fully independent safety barriers.

5.5 Human and organizational factors

A frequency change is cognitively small but operationally persistent. Controllers, pilots, dispatchers and neighboring units may recall the old value from memory; databases may update on different cycles; and an uncontrolled parallel operation can create conflicting instructions. The 84-day assurance period provides time to observe the decline in legacy calls, validate transfer behavior and correct data inconsistencies. This is consistent with ATM safety literature emphasizing work-as-done and system interfaces (Patriarca et al., 2016; Woltjer et al., 2015).

5.6 Generalizability

The workflow is transferable to other regional airports because it distinguishes universal rules from local evidence. AFI allotment, ICAO DOC criteria, ITU unwanted-emission definitions and SMS change-management principles are generic. Coordinates, service-volume geometry, EIRP, terrain, neighboring assignments, equipment architecture and operational interfaces are site-specific. The method is especially useful where spectrum records are fragmented: it allows an ANSP to produce a defensible preliminary case while explicitly preserving conditions that only the regulator or field measurements can close.

5.7 Study limitations

The nearest cochannel records used for screening must be confirmed through official Frequency Finder and COM List 3 data.

No measured transmitter power, EIRP, antenna pattern, receiver sensitivity or terrain-based propagation result was available.

No flight-inspection or operational trial dataset was available; coverage conclusions are therefore requirements, not demonstrated performance.

Public databases contained divergent values for several stations and were not used as final regulatory evidence.

The transition duration is a project safety decision structured around AIRAC cycles, not an ICAO-mandated fixed period.

The proposed NSI is a descriptive index and must not be interpreted as a substitute for ICAO compatibility calculations.

6. Recommended validation and doctoral-level extension

To convert the preliminary case into a fully empirical publication and implementation dossier, the following measurement and analysis programme is recommended:

Work package	Minimum content	Primary output
WP1 - Official spectrum coordination	Frequency Finder and COM List 3 export; AFI and neighboring-State coordination	Approved assignments and conflict closure
WP2 - RF site characterization	TX power, feeder/filter loss, antenna pattern, EIRP, receiver parameters, spectrum scan	Traceable RF baseline
WP3 - Propagation modelling	ITU-R P.528 predictions for representative heights, terrain profiles and availability percentages	Predicted field-strength and link-margin maps
WP4 - Field trials	Ground and flight measurements in CTR/TMA sectors and movement area	Measured DOC compliance and shadow-zone closure
WP5 - CEM stress testing	Simultaneous transmit, IM3, harmonics, blocking, squelch, passive intermodulation	Signed EMC acceptance report
WP6 - Operational simulation	TWR/APP/GND transfer, wrong-frequency, ComLoss, emergency and rollback scenarios	Human-performance and procedure evidence
WP7 - Post-J data analysis	Availability, legacy-call rate, transfer errors, interference, corrective actions	J+84 safety-review evidence

A future multi-airport extension could formulate the assignment problem as a graph G=(V,E), in which each station-service volume is a vertex and interference relationships define edges. Channel selection would then minimize spectrum cost subject to regulatory, DOC, net-filter-discrimination and safety constraints, providing a bridge between this case-study workflow and the broader optimization literature.

7. Conclusions

This study demonstrates that aeronautical VHF modernization should be treated as a coupled spectrum-engineering and safety-management problem. For Kolwezi Airport, 118.900 MHz (TWR), 120.400 MHz (APP-I) and 121.700 MHz (AS/GND) are the preferred candidates. Conservative screening gives positive cochannel margins of 101.0, 439.6 and 558.7 NM and NSI values of 1.49, 1.81 and 16.96. These results support coordination but do not constitute assignment authorization.

The decisive residual issues are the actual DOC and EIRP, the completeness of official regional assignment data, site-specific propagation, and co-sited EMC. Third-order products in the VOR/ILS localizer band make filters, antenna isolation and measured stress testing mandatory. The operational transition should establish 118.900 MHz as the sole normal Tower frequency at T0, retain 118.300 MHz only as monitored fallback and redirection for 84 days, and permit extension to 168 days only through a documented safety review.

The integrated framework is suitable for regional ANSPs because it is explicit about uncertainty: it converts missing measurements into conditions for approval rather than concealing them behind nominal frequency-distance calculations. Final implementation requires official coordination, approved technical parameters, objective test evidence, consistent AIS publication, trained personnel and formal acceptance of residual risk.

Author contributions (Credit)

Billy Diabasenga Kusuamina: Conceptualization, operational requirements, methodology, investigation, project administration, writing - original draft, writing - review and editing. Contributing authors : review, editing and academic supervision.

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Declaration of competing interests

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work.

Data availability

The geospatial screening data and derived calculations are reported in the article. Official COM List 3/Frequency Finder exports, licensed ICAO publications, equipment configuration data and future RF measurements may be subject to regulatory, licensing or operational-access restrictions.

Ethics and safety statement

No human-subject experiment was conducted. Operational implementation is prohibited until regulatory assignment, technical validation, safety approval and AIS publication have been completed.

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