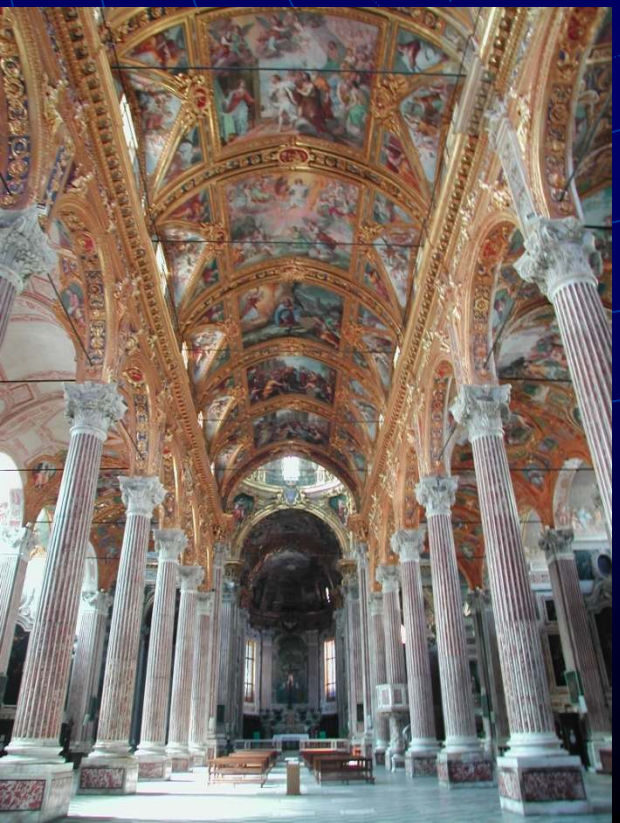
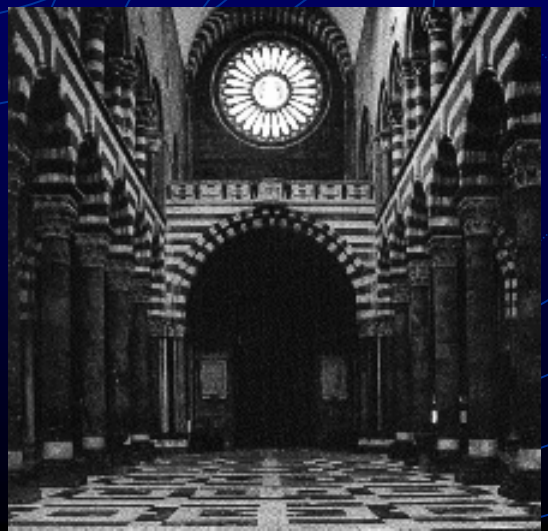
Churches as auditoria: analysis of acoustical parameters for a better understanding of sound quality

Paola Ricciardi

Department of Civil Engineering and Architecture, University of Pavia, Via Ferrata, 1 - 27100 Pavia, Italy
Tel: +39 0382 985303e-mail: paola.ricciardi@unipv.it





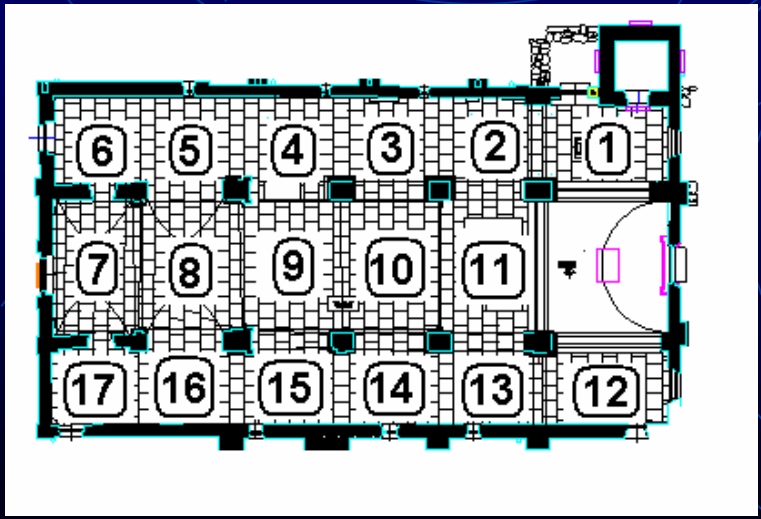
The research

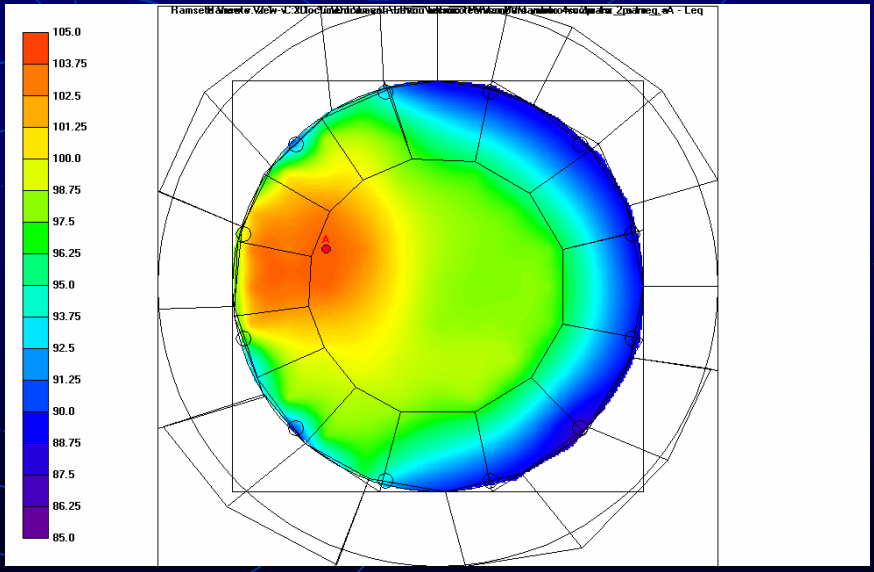
The acoustic characterisation of buildings for music performances:

Worship buildings can be used as auditoriums?

Theoretical models and software

Experimental measurements





The aim and the results

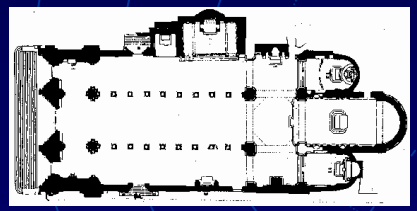
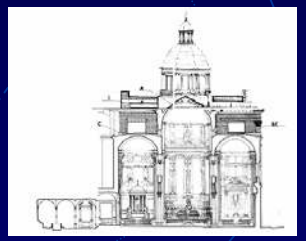
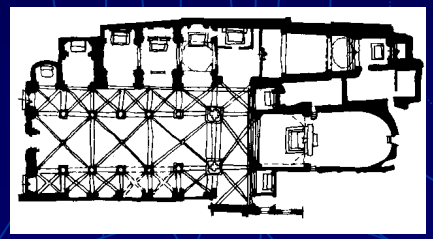
A contribution to the data collection on the acoustic performance of the Churches aimed to their use as auditorium

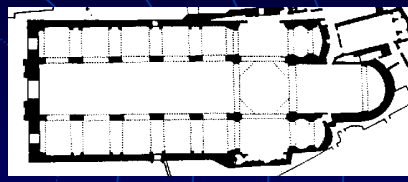
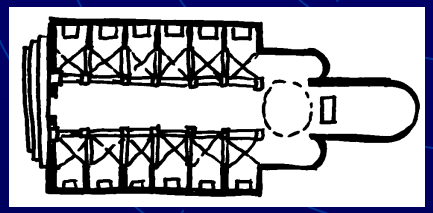
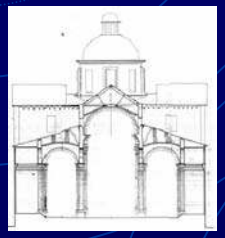
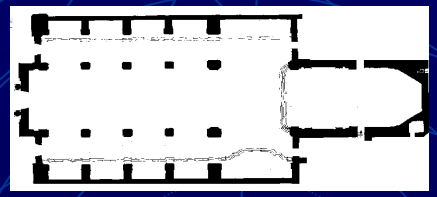
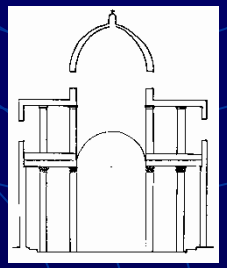
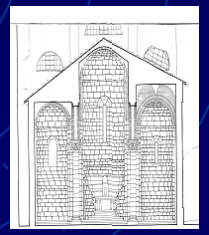
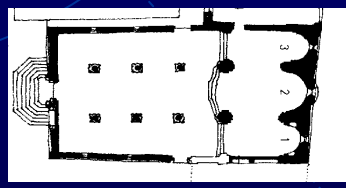
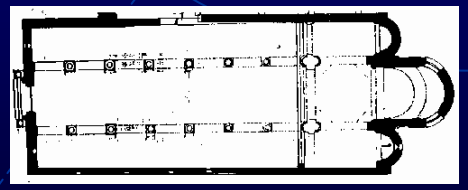
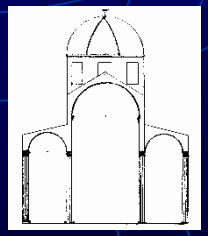
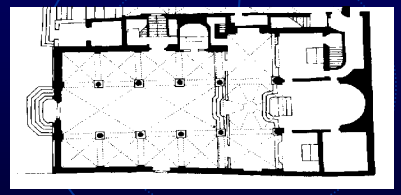
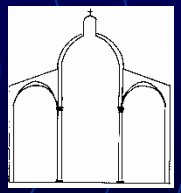
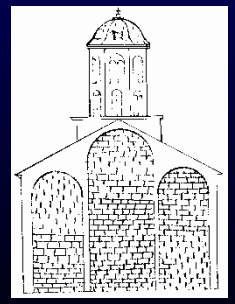
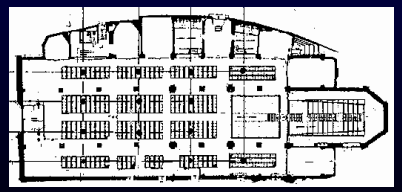
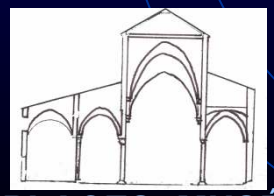
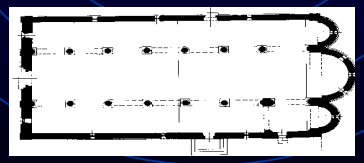
Deeper knowledge on the influence of the internal geometric complexities on the acoustic field, such as:

- **lateral chapels,**
- **coupled rooms,**
- **diffusive elements or obstacles to the sound propagation,**
- **orientation of surfaces,**
- **convex surfaces than can create sound concentration**

The Churches

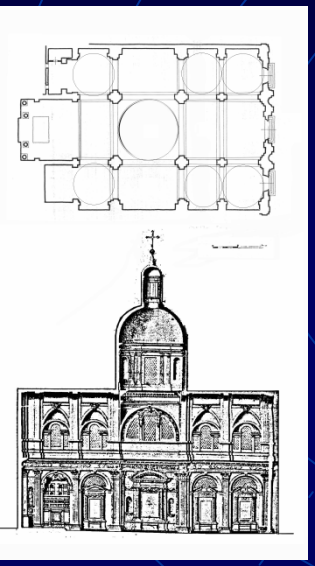
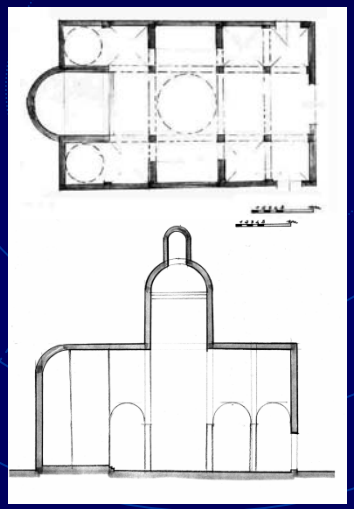
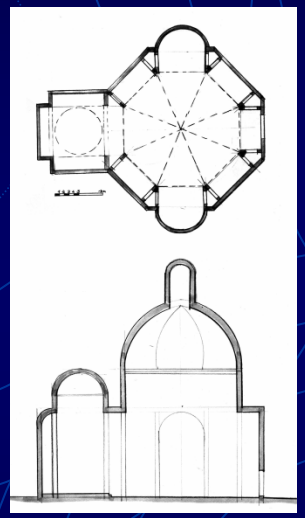
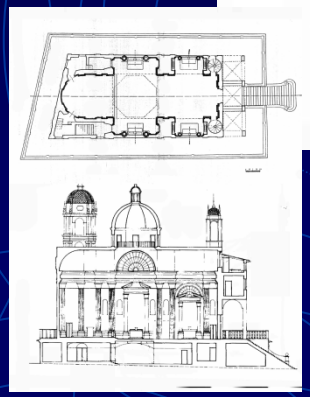
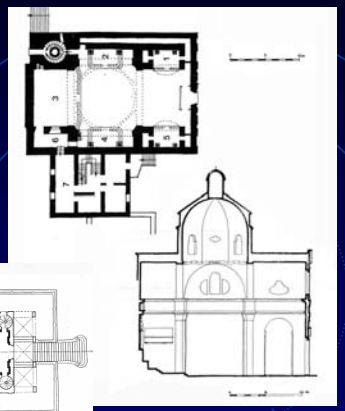
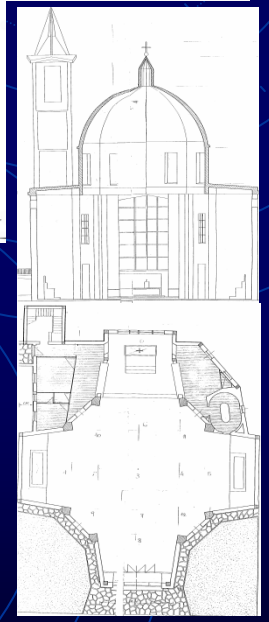
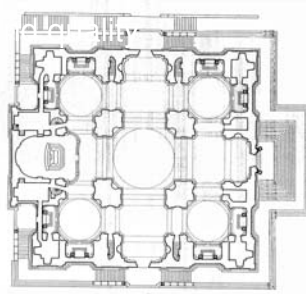
10 Churches - rectangular plan (nave – 2 aisles) with/without lateral chapels and/or cupolas, volume = 2183 - 43540 m^3

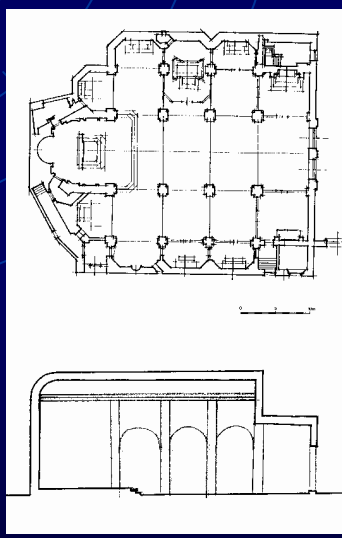
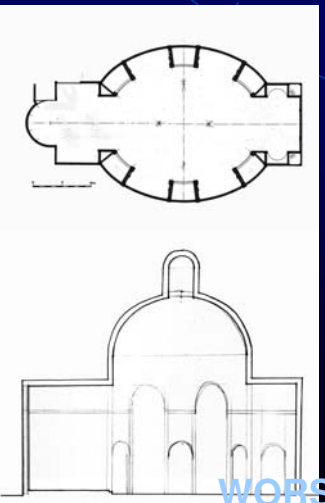
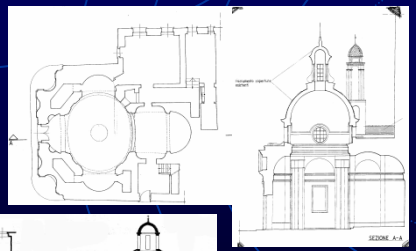
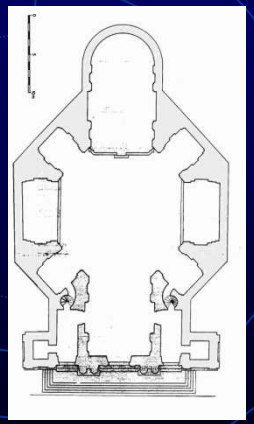
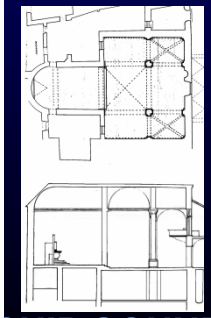
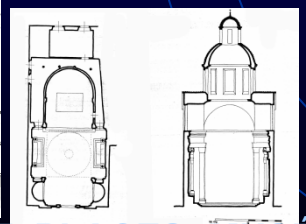
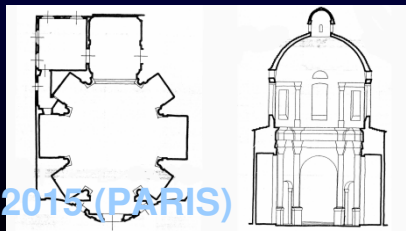





The Churches

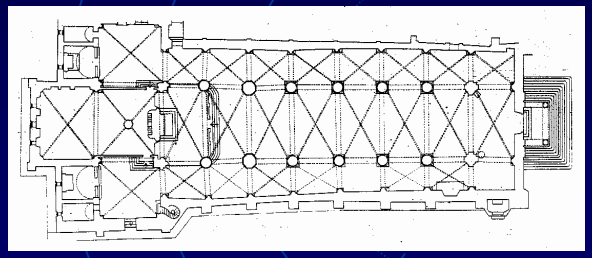
14 Churches: central plan with/without dome/cupolas volume = 1409 - 43756 m^3

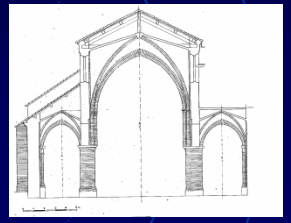








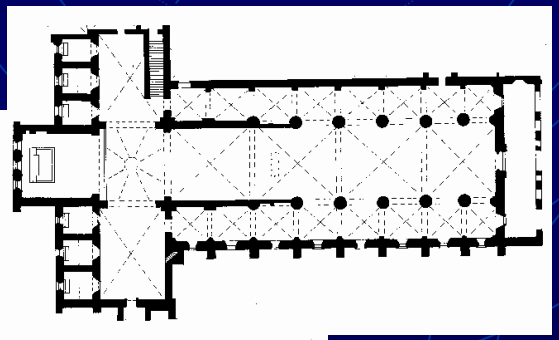








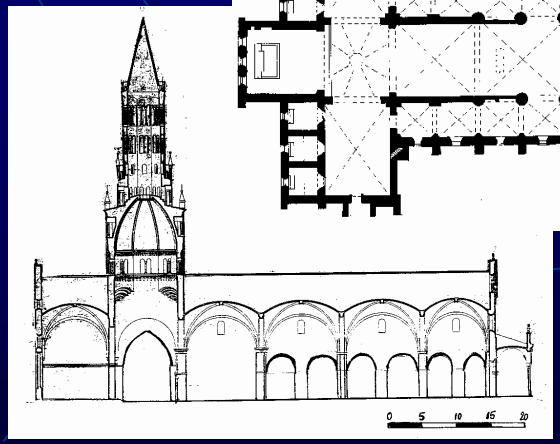
The Churches

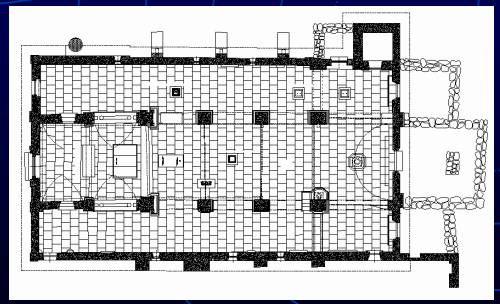
6 Medieval Cistercian Abbeys
volume = 3390 - 14970 m³

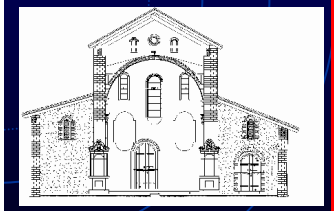








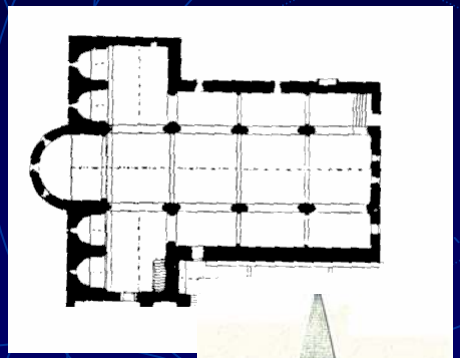


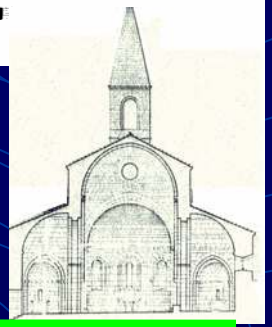


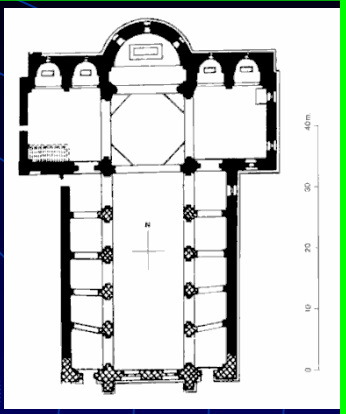
Northern Italy

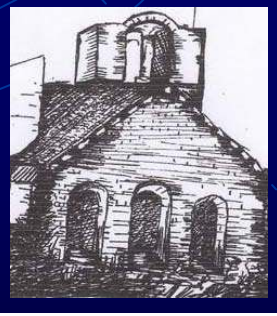
Southern France

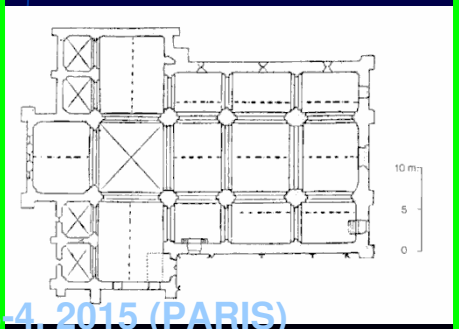
The 3 Provençal Sisters











MEASUREMENTS – longitudinal plan

Measured data in 10 Italian churches (XI-XVI sec., V=2200÷43.000 m^3)

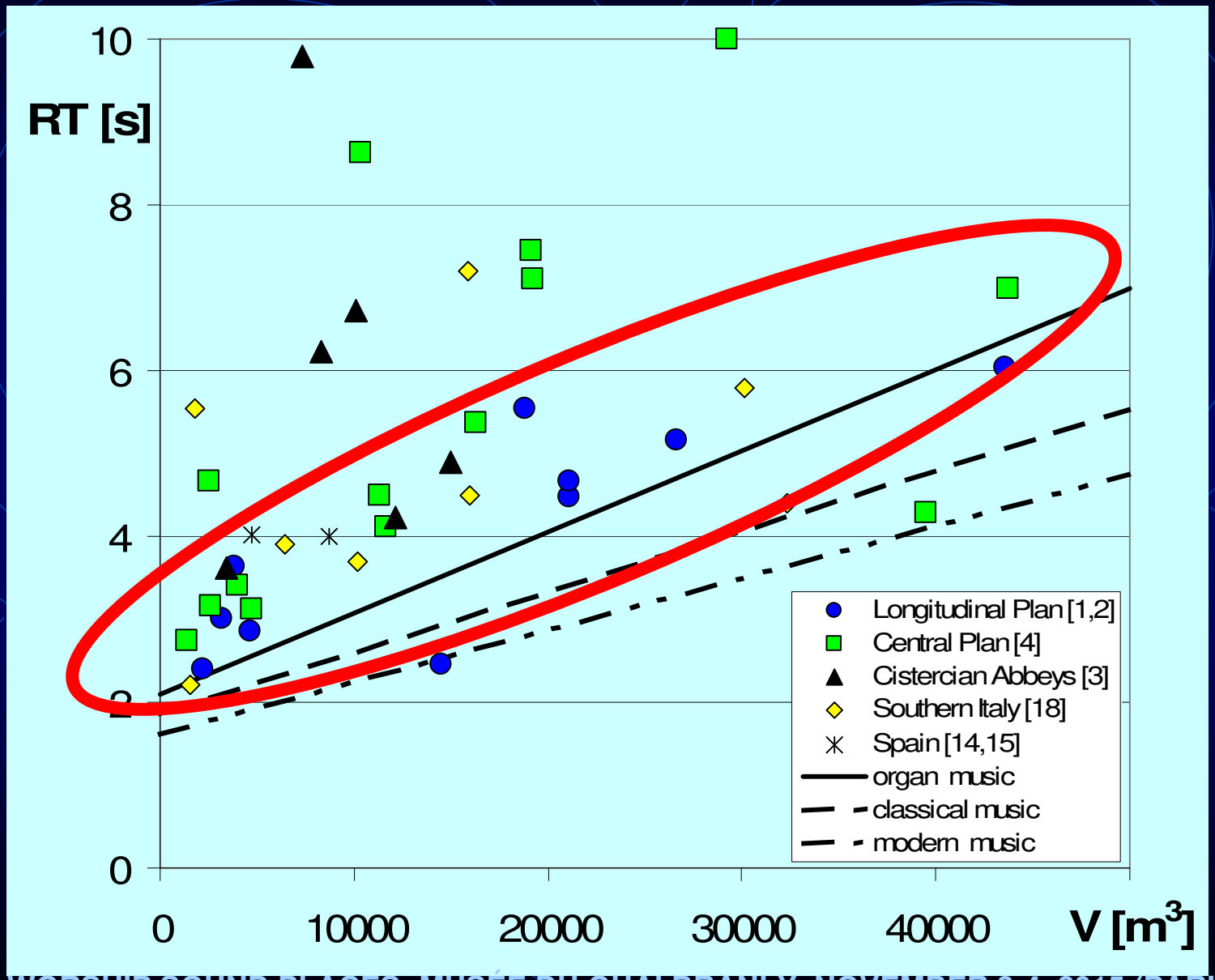
Church	Points	V [m^3]	S [m^2]	C50 [dB]	C80 [dB]	D50 [%]	EDT [s]	RT20 [s]	RT30 [s]	TS [ms]
S.Lorenzo	17	43540	2040	-9.2	-6.7	16.3	5.1	5.1	--	387.1
SS.Annunziata	27	26603	1815	-8.8	-6.5	17.6	4.7	4.2	--	362.8
S.M.Castello	26	21100	1755	-9.8	-6.5	12.9	3.8	3.6	3.6	308.2
N.S.Consolazione	15	18842	1065	-10.2	-7.7	14.7	4.5	5.2	4.6	368.9
S.Agostino	24	14500	1223	-8.9	-5.2	15.5	2.7	2.5	2.3	227.8
S.M.Vigne	18	14000	1308	-8.5	-5.8	17.5	3.6	4.1	3.6	296.2
S.Donato	21	4650	340	-7.6	-4.1	18.4	2.3	2.3	2.4	193.2
S.Matteo	12	3211	338	-6.5	-3.3	20.7	2.3	2.4	2.5	185.1
S.Siro di Struppa	11	3827	383	-7.4	-3.5	18.5	2.6	2.8	2.8	202.0
SS.Cosma e Damiano	12	2183	241	-6.3	-2.8	22.3	2.0	2.0	2.2	164.9

MEASUREMENTS – CENTRAL PLAN

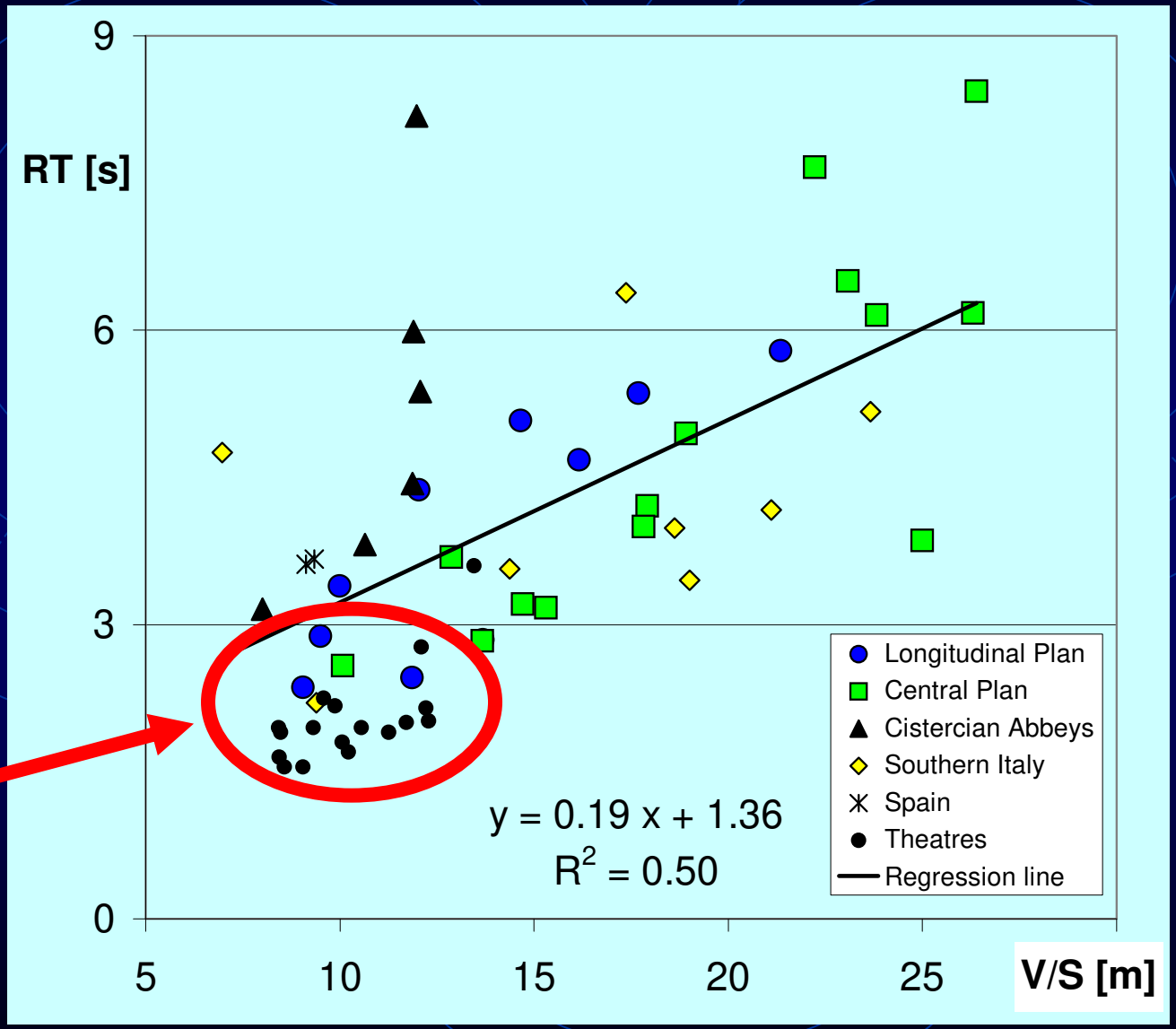
Measured data in 10 Italian churches (XI-XVI sec., V=2500÷49.000 m^3)

Church	Measur. points	V [m^3]	S_{tot} [m^2]	C50 [dB]	C80 [dB]	D50 [%]	EDT [s]	RT20 [s]	RT30 [s]	TS [ms]
S.Maria Assunta	28	49471	1837	-10.53	-8.29	11.58	6.12	6.16	5.61	467
S.Zita	12	29220	1107	-11.67	-9.54	8.75	8.79	8.77	8.90	666
Chiesa del Gesù	16	25595	1580	-9.22	-6.74	14.38	3.97	3.86	3.05	314
N.S.del Rimedio	12	18040	731	-9.19	-7.21	12.17	5.60	6.19	6.20	411
S.Maria Immacolata	18	16262	860	-8.82	-6.79	15.24	4.89	4.95	4.46	365
S.Caterina	17	11650	905	-10.15	-6.81	10.75	3.73	3.69	3.69	297
S.Benedetto	6	4700	307	-9.62	-6.13	11.63	3.13	3.17	3.21	257
S.Croce S.Camillo	10	3955	269	-8.11	-5.59	15.84	3.21	3.21	3.22	252
S.Pietro in Banchi	13	2584	189	-7.79	-4.69	15.16	2.80	2.83	2.87	224
S.Luca	6	2494	140	-8.44	-6.24	14.05	3.77	4.00	4.07	290

Reverberation Time at 500 Hz – Optimal values

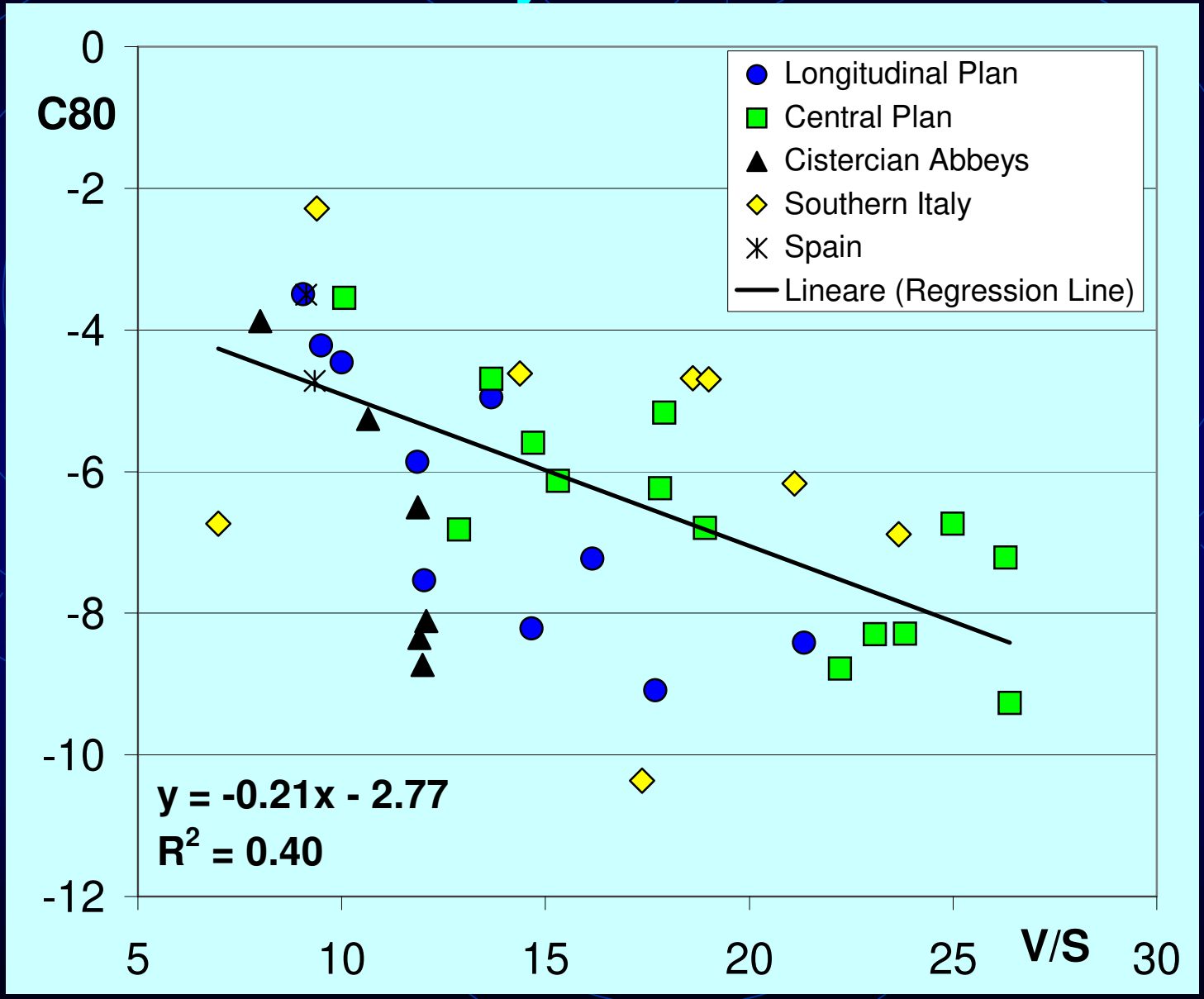


Reverberation Time

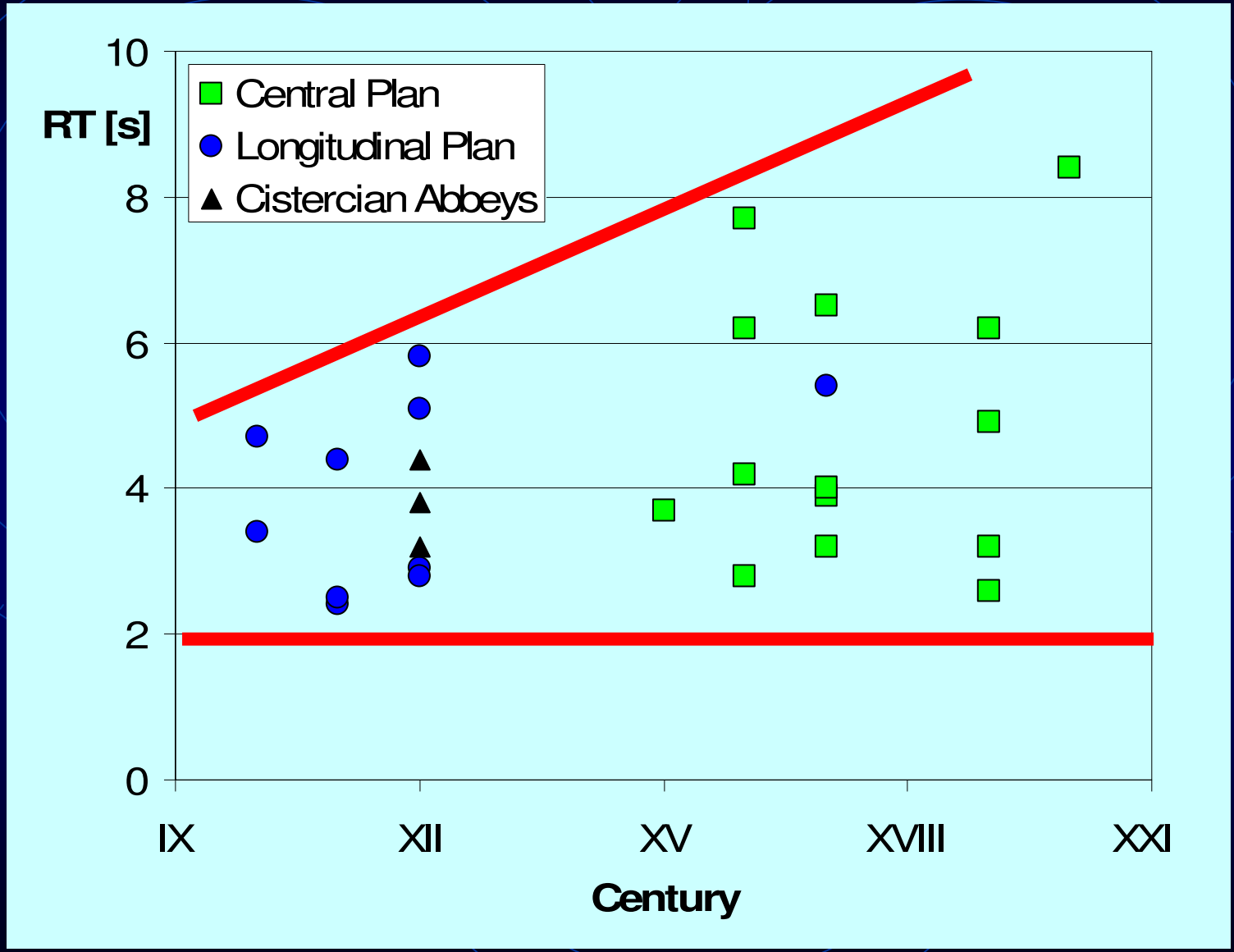


Theatres

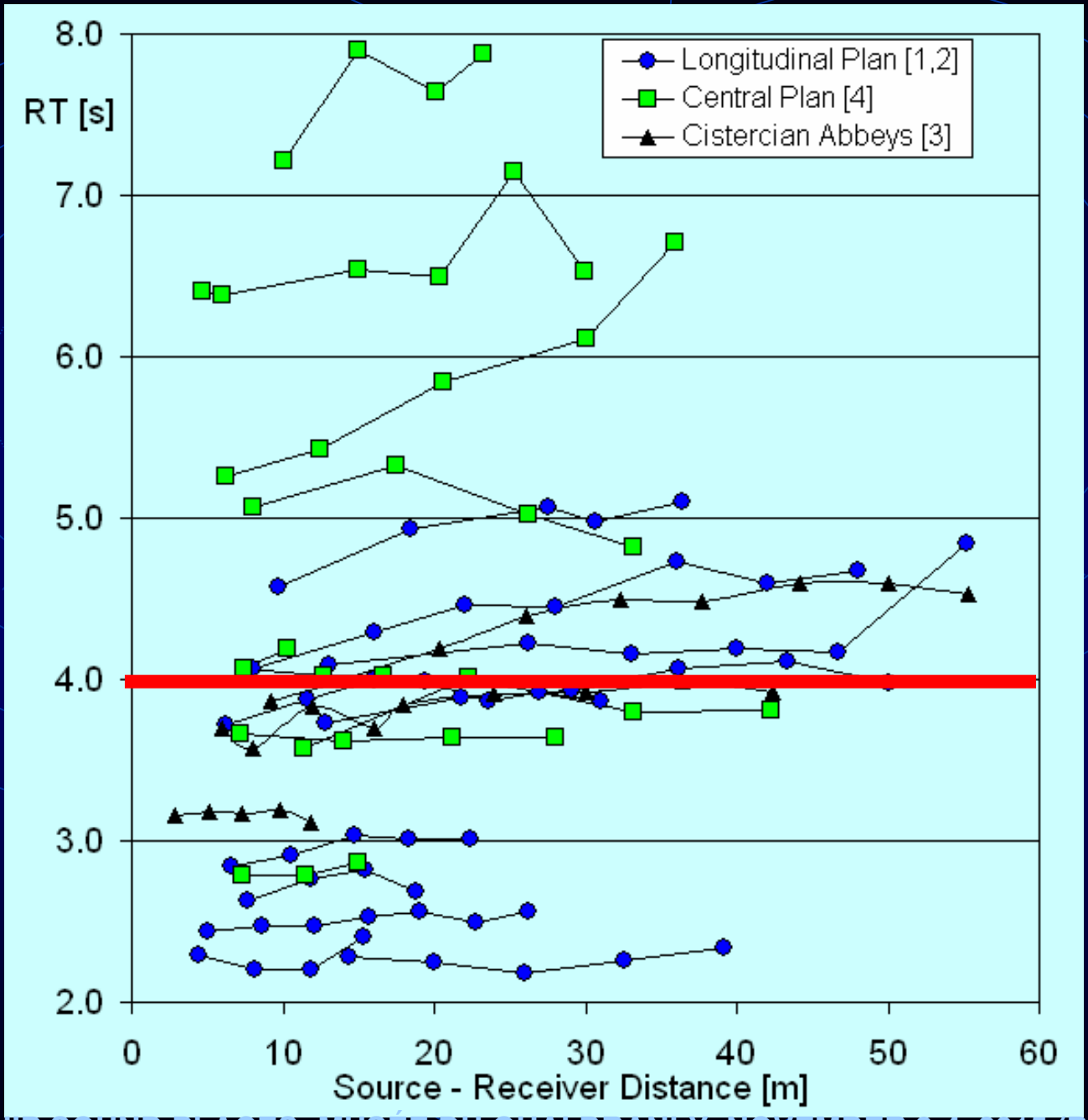
Clarity Index C80



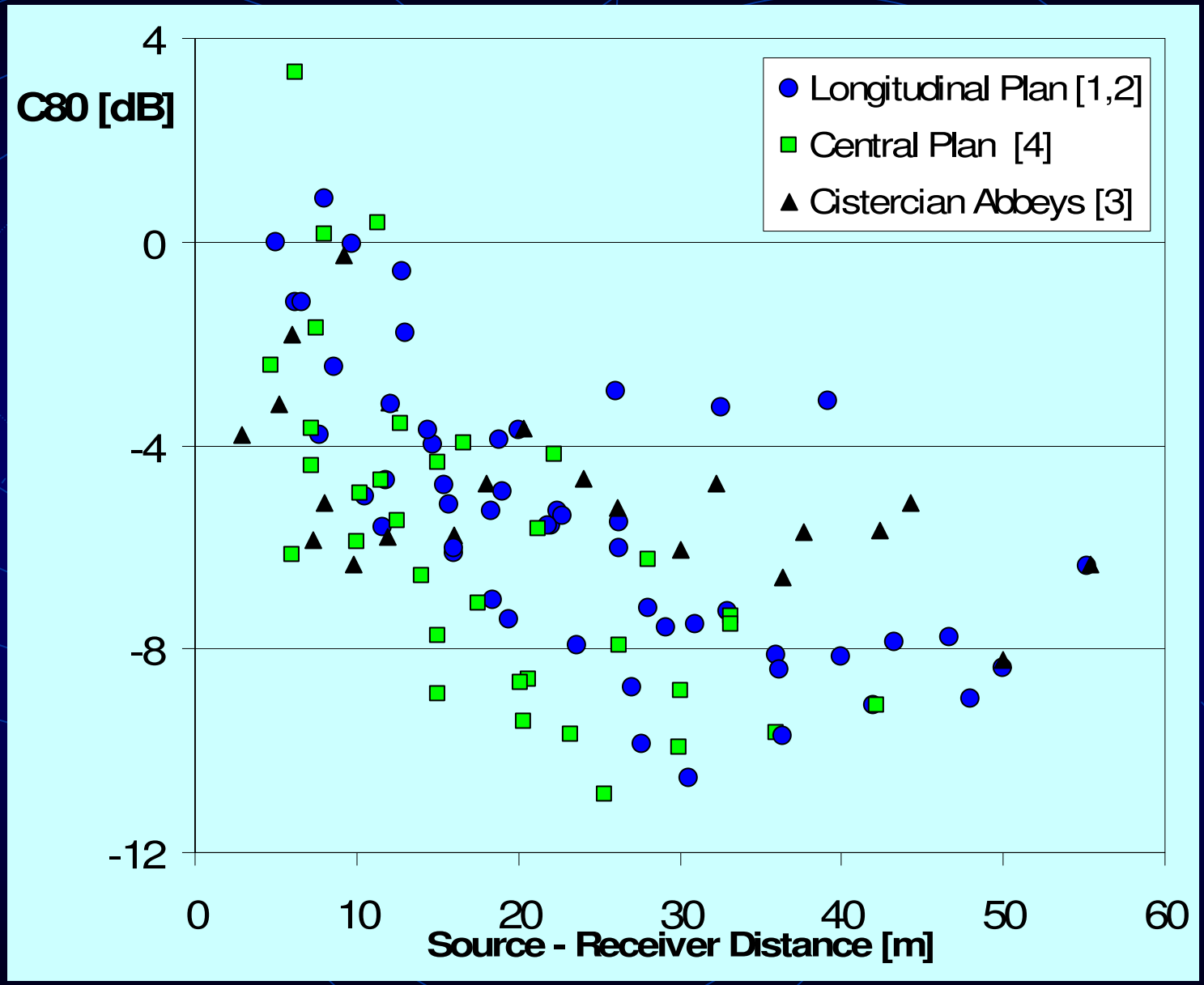
RT – Century of construction



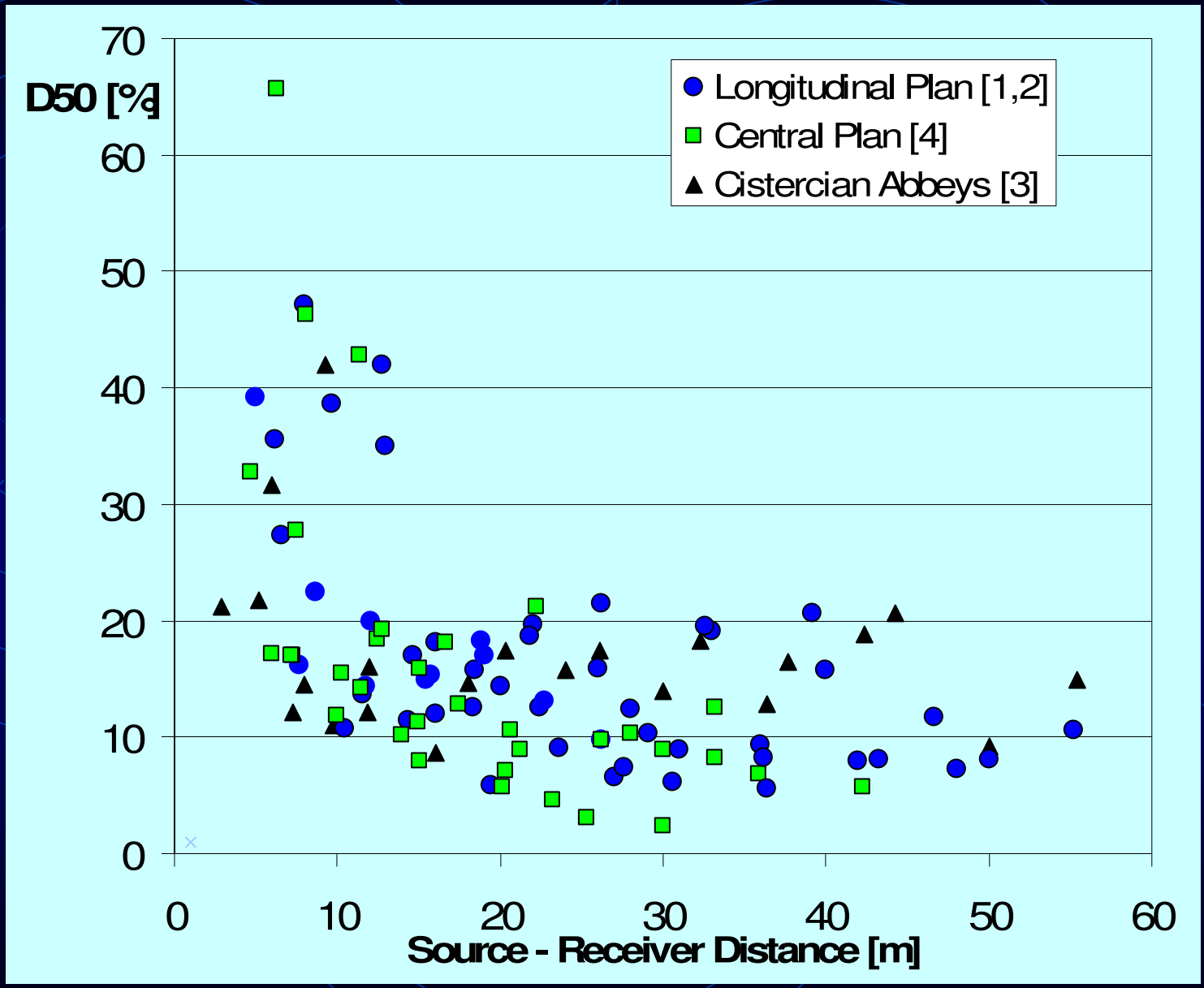
Mean RT as function of SR distance



C80 as function of SR distance



D50 as function of SR distance



CONSIDERATIONS

Worship buildings with more articulated volumes (Gesù Church, with 7 cupolas) are more adequate for music performances.

For this aim, almost all the central plan Churches are not appropriate, unless some acoustic corrections are realised.

The RT distribution for Churches with rectangular plan and two aisles without cupolas was significantly different from the ones with central plans.

Among these last ones, bigger volume Churches presented more scattered RT values.

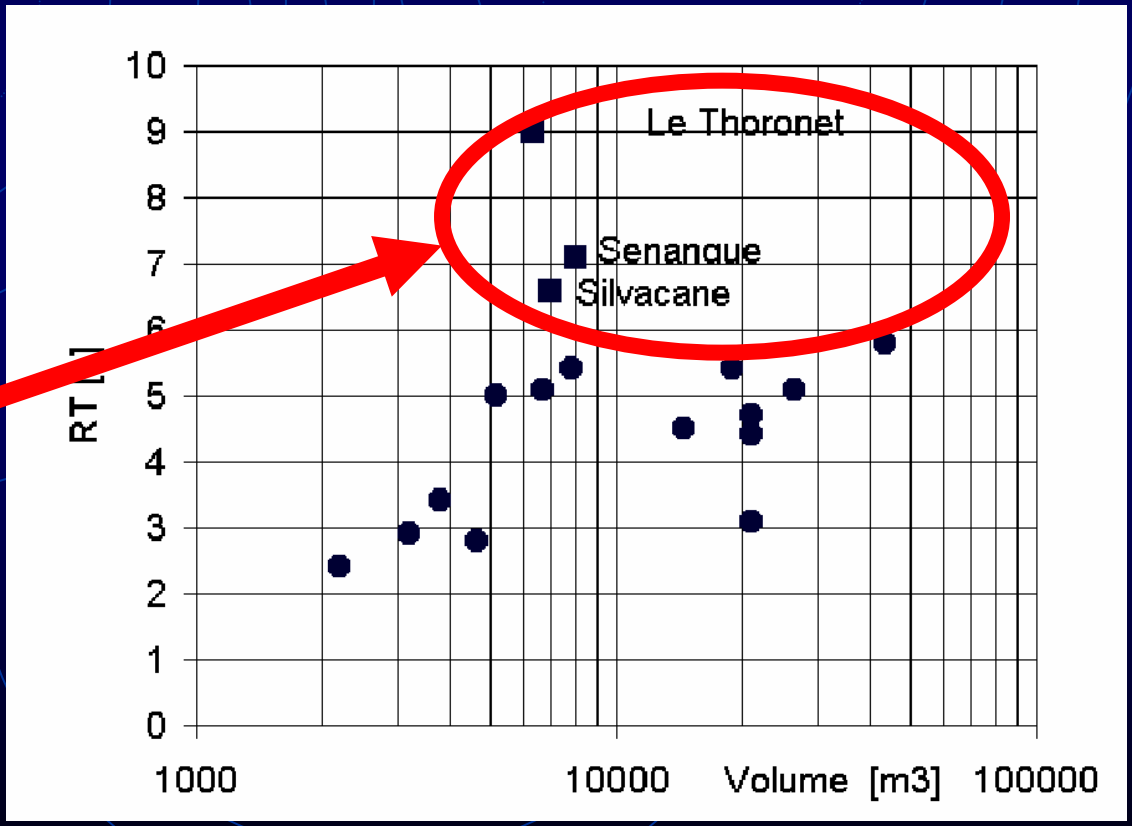
And other considerations….

CONSIDERATION ON THE HISTORICAL PERIOD

In the French Cistercian Abbeys some acoustic features may have been intentionally prosecuted by the Ancient Architects

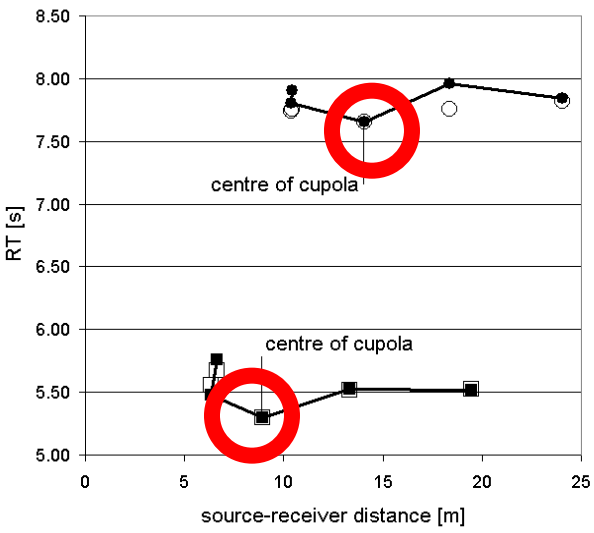
Average values of RT in the range 500-1000 Hz

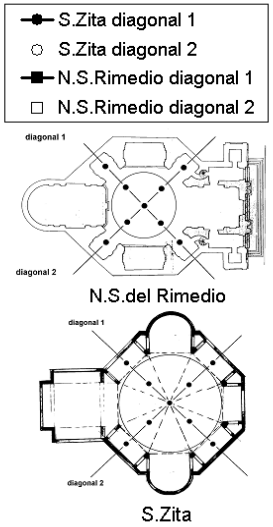
The values are higher than in other churches with almost the same volume

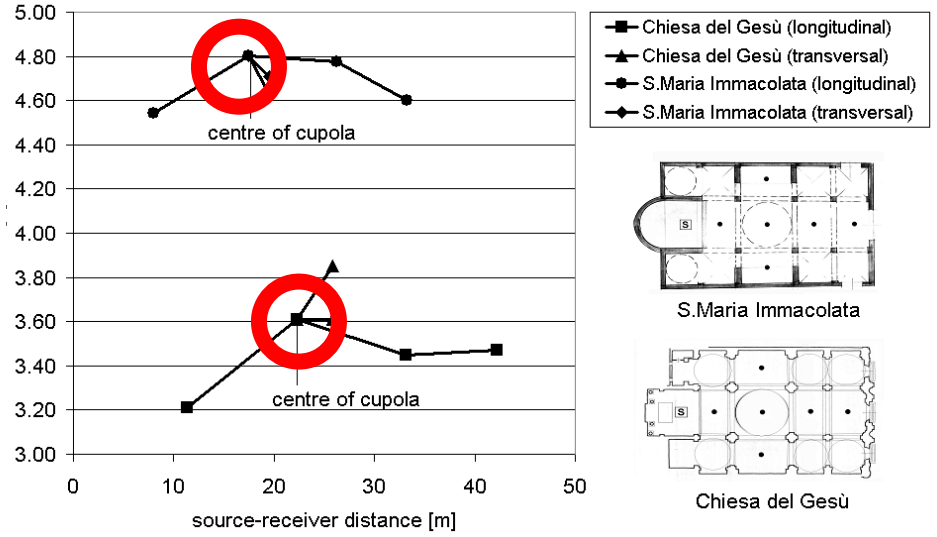


CONSIDERATION ON THE EFFECT OF THE GEOMETRY ON RT

The RT under the dome is lower in larger volume churces, but higher in smaller ones



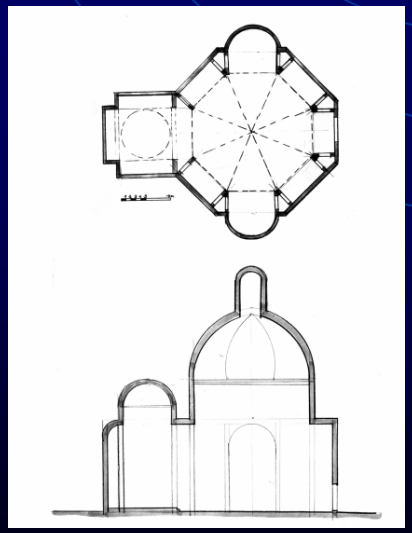


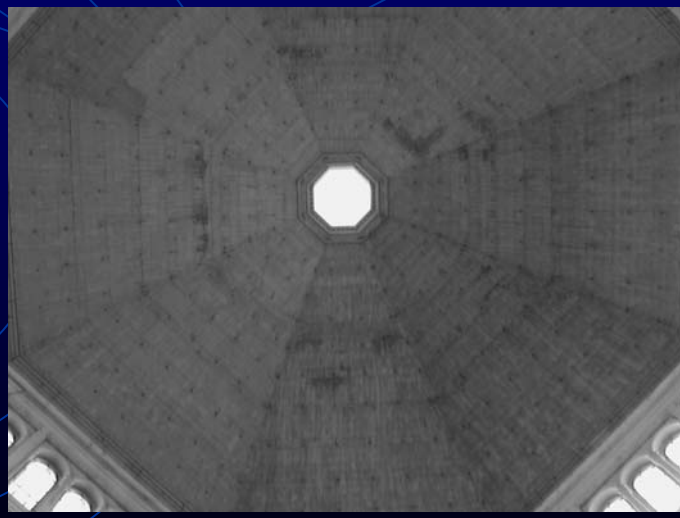


CHARACTERISTICS OF THE CHURCH OF S. ZITA

- Construction of 1874
- Both domes are in reinforced concrete
- Pavement in marble,
- Interior simply painted
- On the pavement
  - Wooden desk

	VOLUME (m^3)	SUPERFICIE (m^2)	ALTEZZA (m)
Cupola grande	3619	904	12.3
Tamburo cupola	3850	620	7.7
Tot. Cupola grande	7588	1649	20
Lucernario	119	125	10
Cupola minore	710	320	9.5
Totale cupole	8298	1969	30
pavimento		1180	
Camera principale	21600	(laterale) 2650	18.3
TOTALE	29898	6389	48.3
Sup. connessione grande		500	
Sup. connessione piccola		92	
Sup. connessione totale		592	



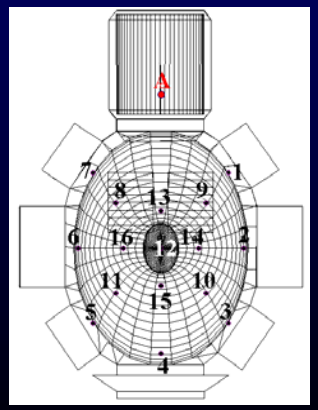


CHARACTERISTICS OF THE CHURCH OF S. GIORGIO

- The period of construction is around 1695
- Pavement in marble,
- Interior higly decorated

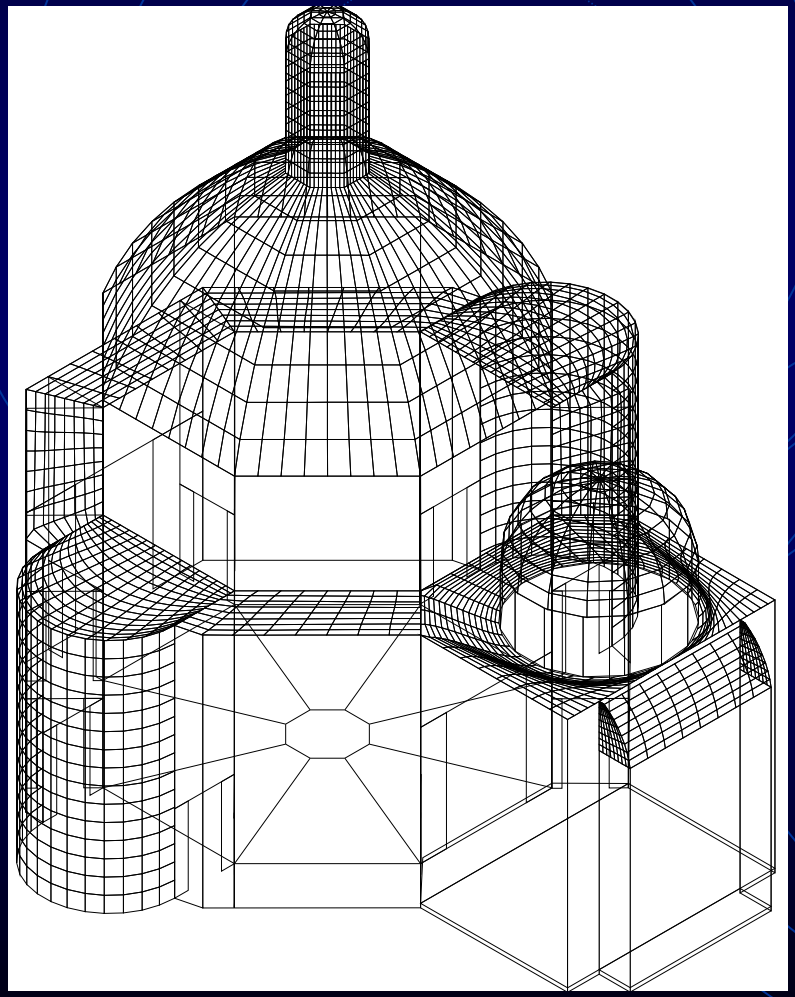
	VOLUME (m^3)	SUPERFICIE (m^2)	ALTEZZA (m)
Cupola	540	280	5.8
Tamburo cupola	1833	560	13
Tot. Cupola	2373	840	18.8
pavimento		300	
Camera principale	3510	1200	11.7
TOTALE	5885	2500	30.5
Sup. connessione		141	

- Sul pavimento panche di legno

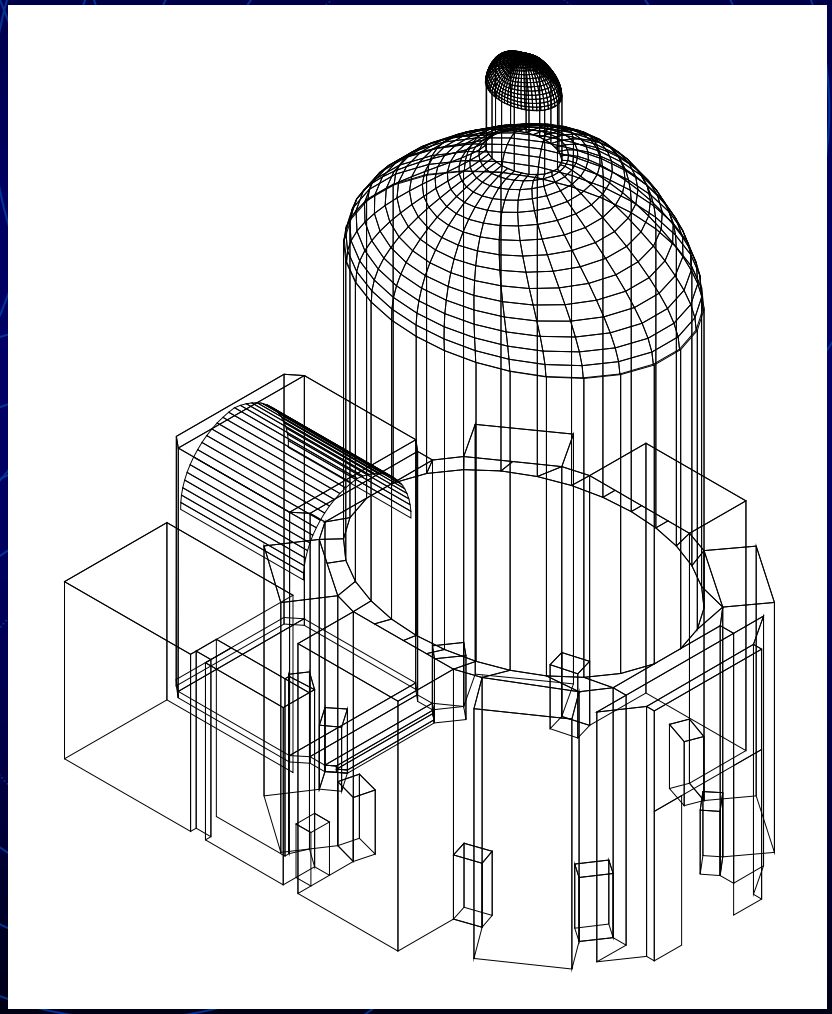


TRIDIMENSIONAL MODELS FOR THE SIMULATION

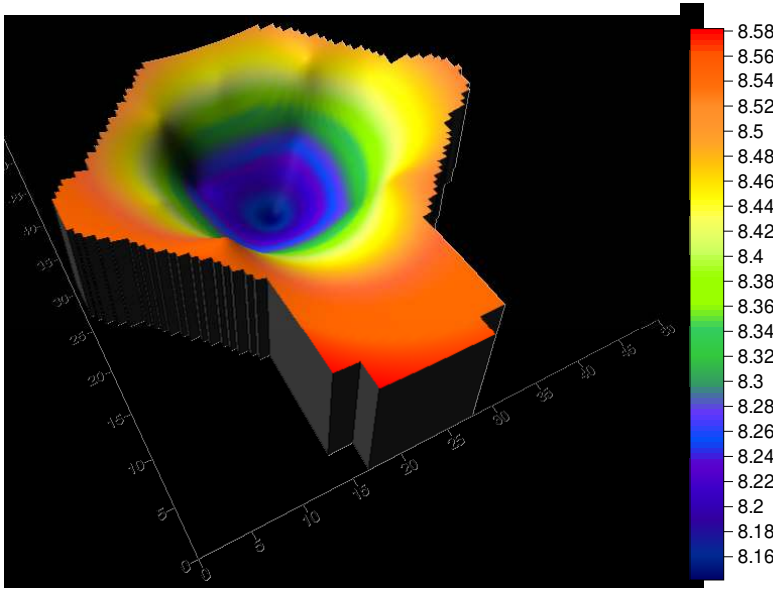
S.Zita



S. Giorgio

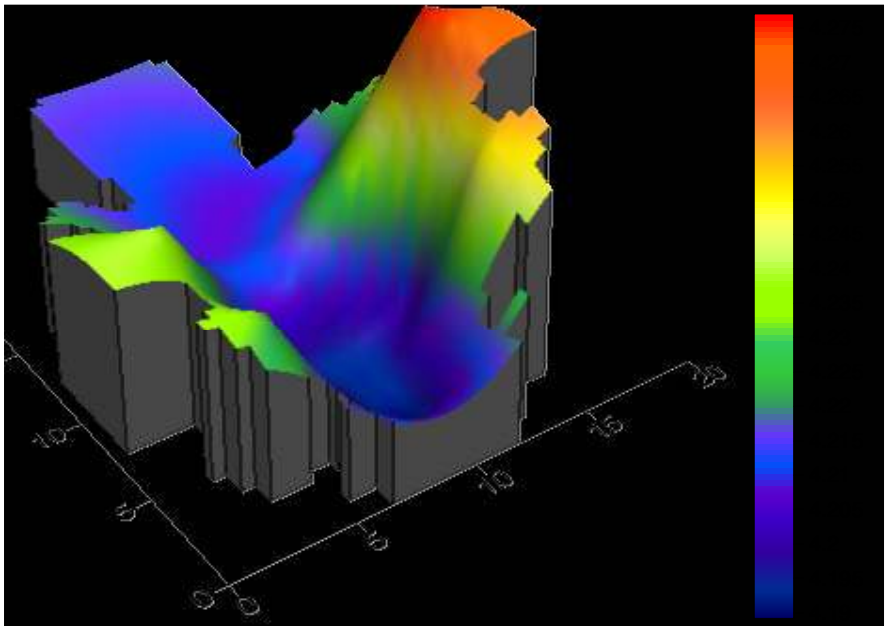


SIMULATIONS RESULTS



SPATIAL DISTRIBUTION OF TR_{20} IN THE FREQUENCY RANGE 125 Hz – 4 kHz FOR

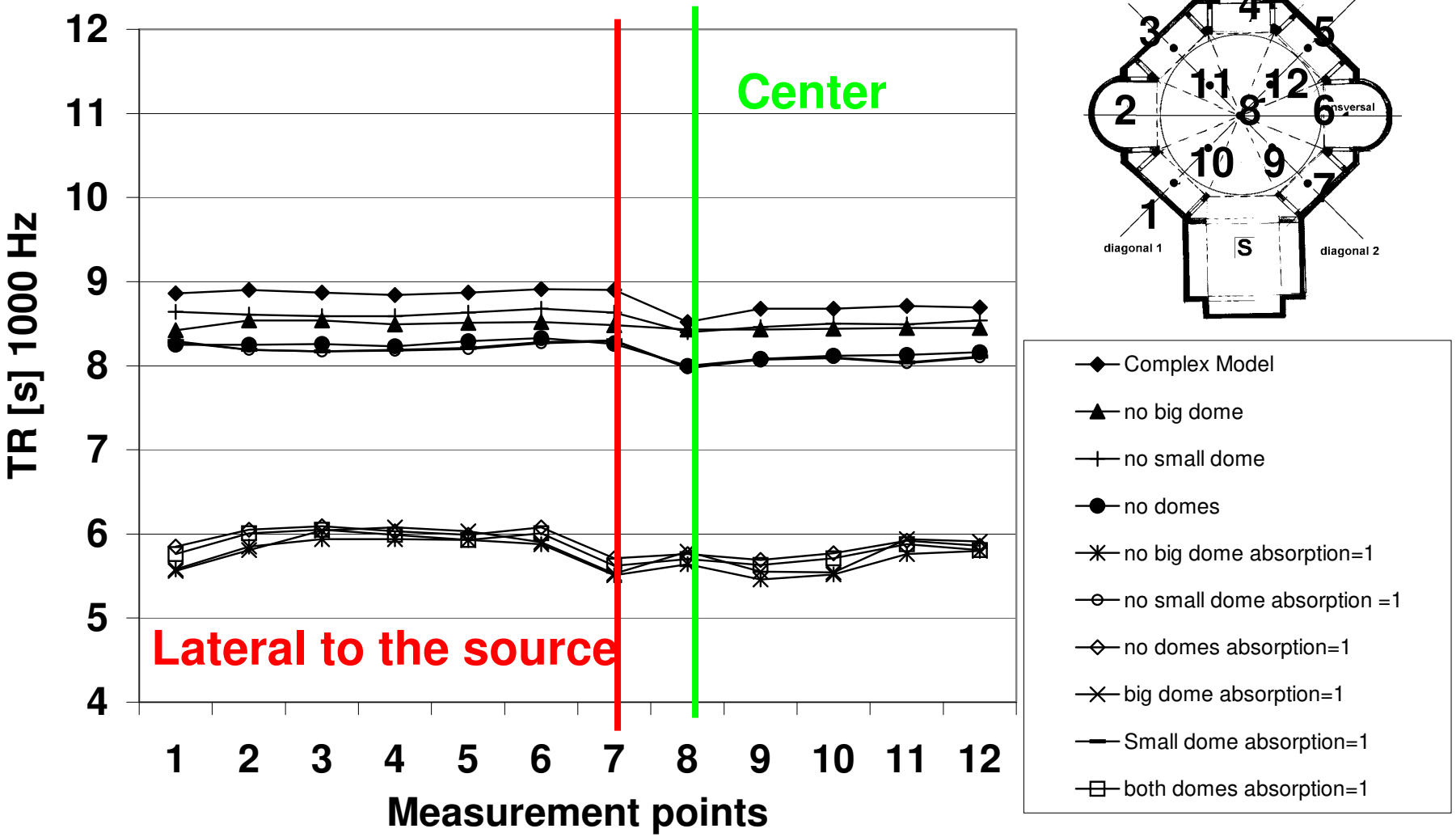
S. Zita



SPATIAL DISTRIBUTION OF TR_{20} IN THE FREQUENCY RANGE 125 Hz – 4 kHz FOR

S. Giorgio

VARIATION OF THE ABSORPTION COEFFICIENT



For both curches with domes having α >0.3 the minimum of RT disappear with α >0.7 the minimum is reached in the positions near the dome.

CONSIDERATION ON THE MEASUREMENT CAMPAIGN

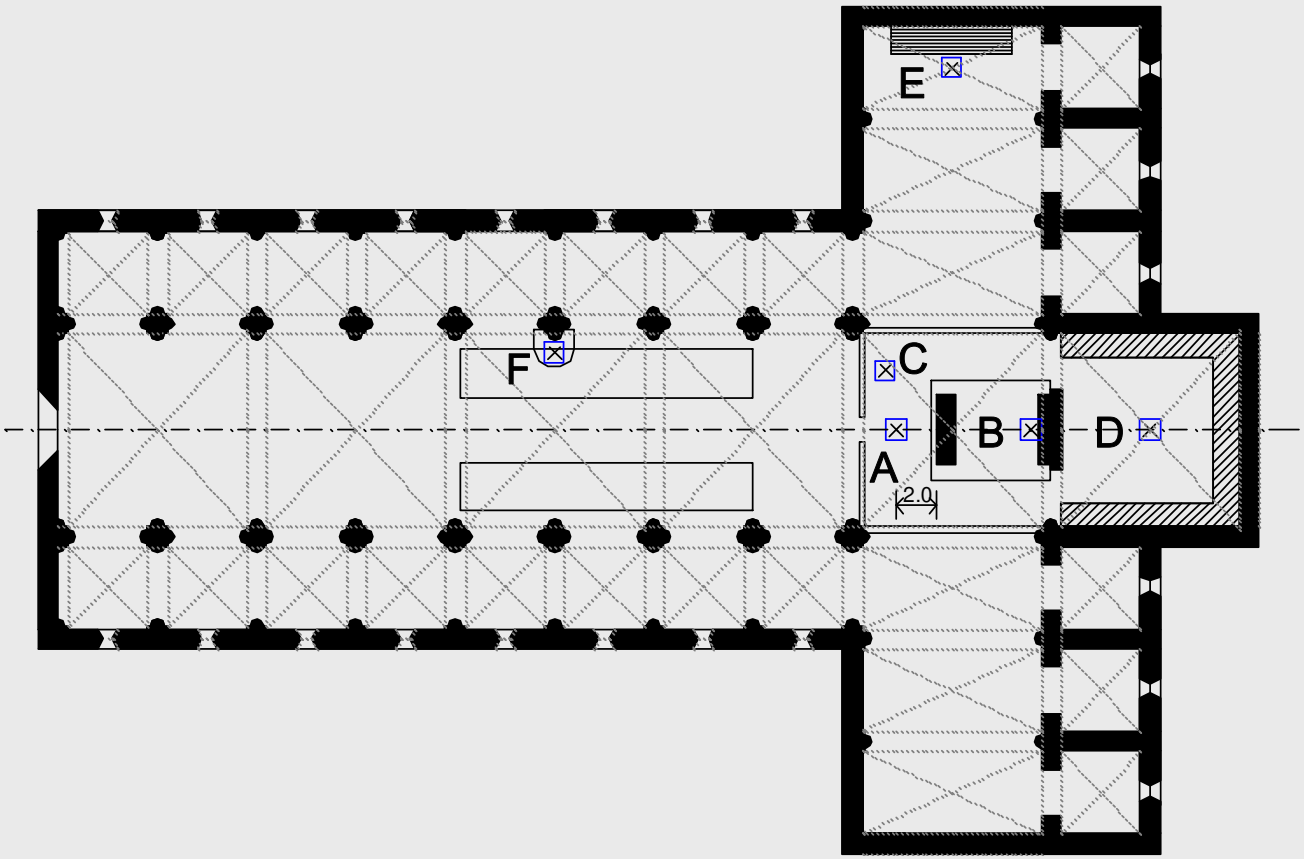
Martellotta F., Cirillo E., Carbonari A., Ricciardi P. (2009). *Guidelines for acoustical measurements in churches.* Applied acoustics, vol. 70, p. 378-388.

- Churches are listening spaces that differ from concert halls and theatres
- Differences are due to the coexistence of speech and music being radiated from several positions that varied with the evolving liturgy
- In addition the room complexity may induce different research teams to place sources and receivers in a different way reducing measurement comparability

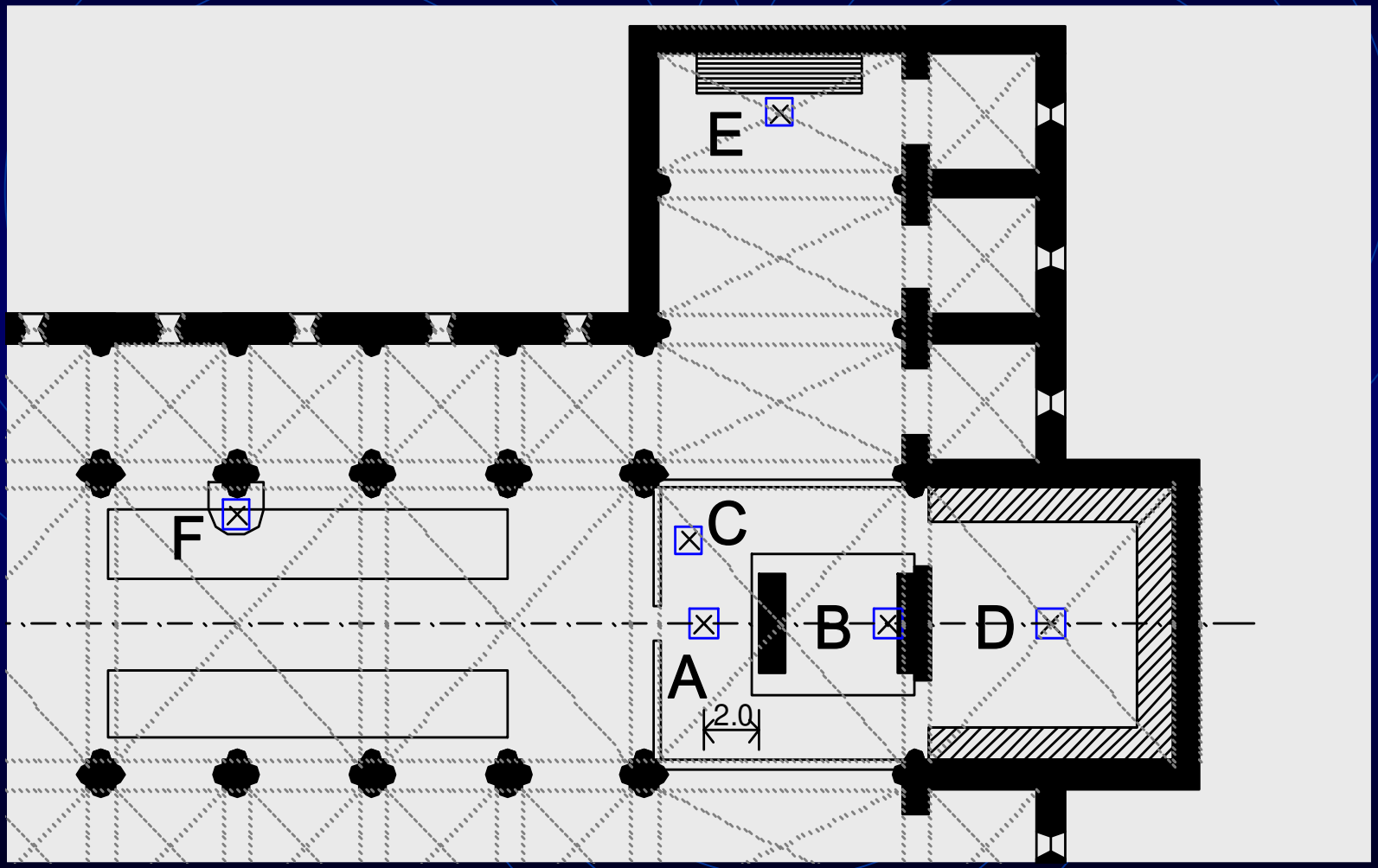
Aims of the proposal

- Define a group of standardised source positions
- Define a minimum number and a rule to place receivers
- Define the equipment characteristics as a function of the measurement purpose

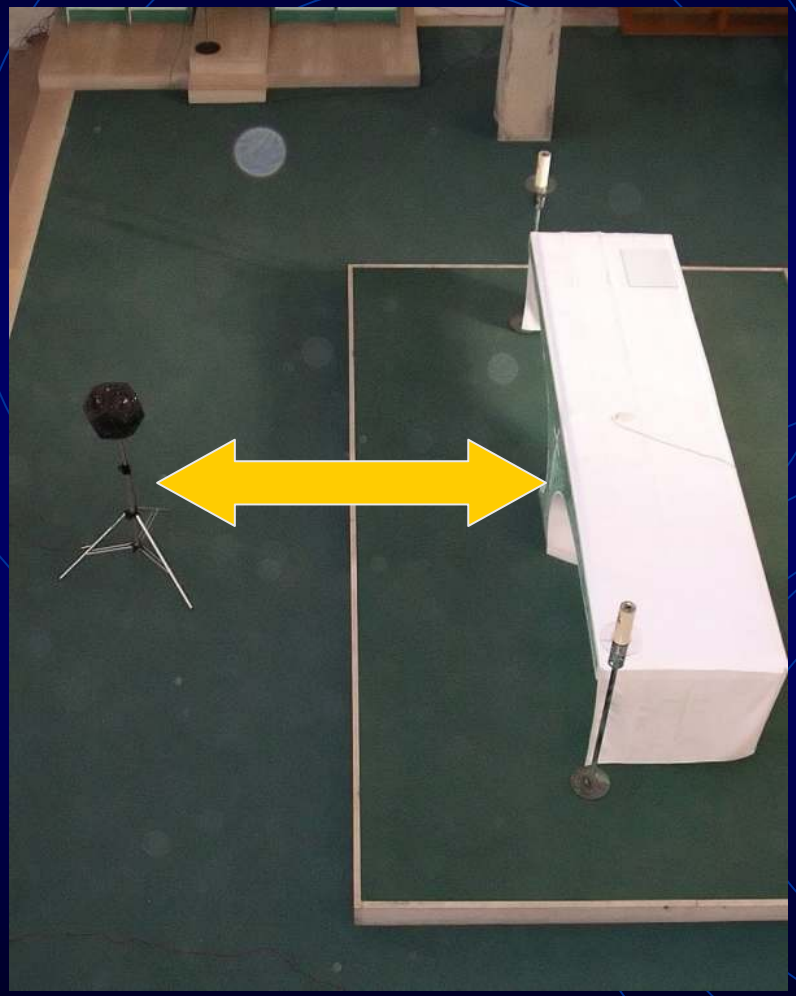
Source placement



Source placement

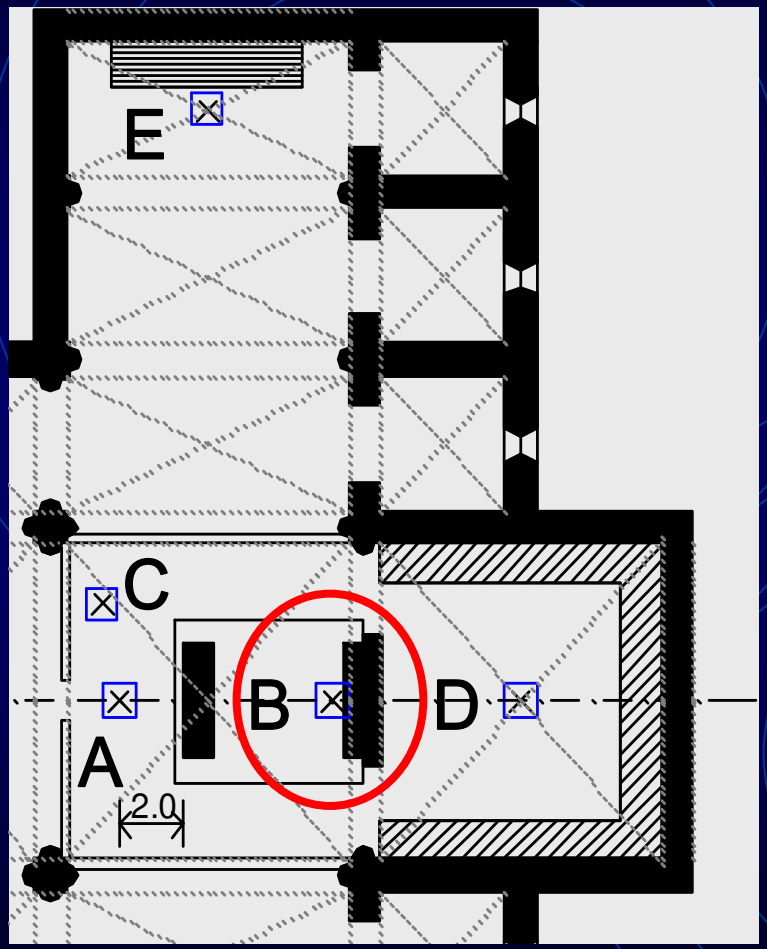


Source placement



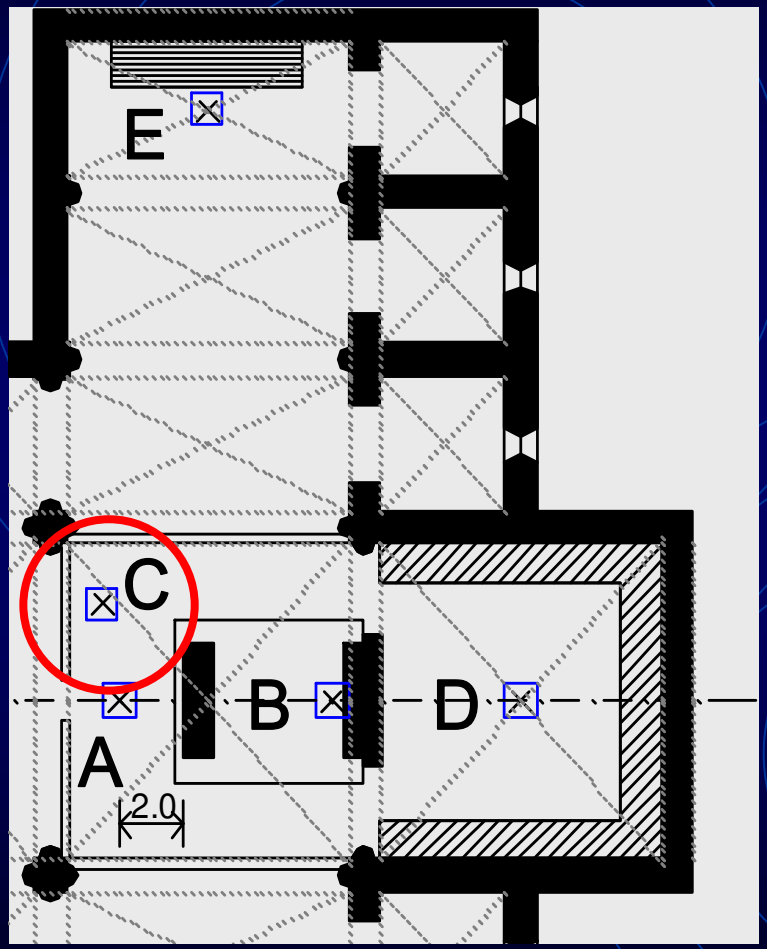
- A) Altar (reference) position
  - At 2 m distance
  - On the symmetry axis (provided that no focussing effects may be detected)
  - At 1.5 m from the floor

Source placement



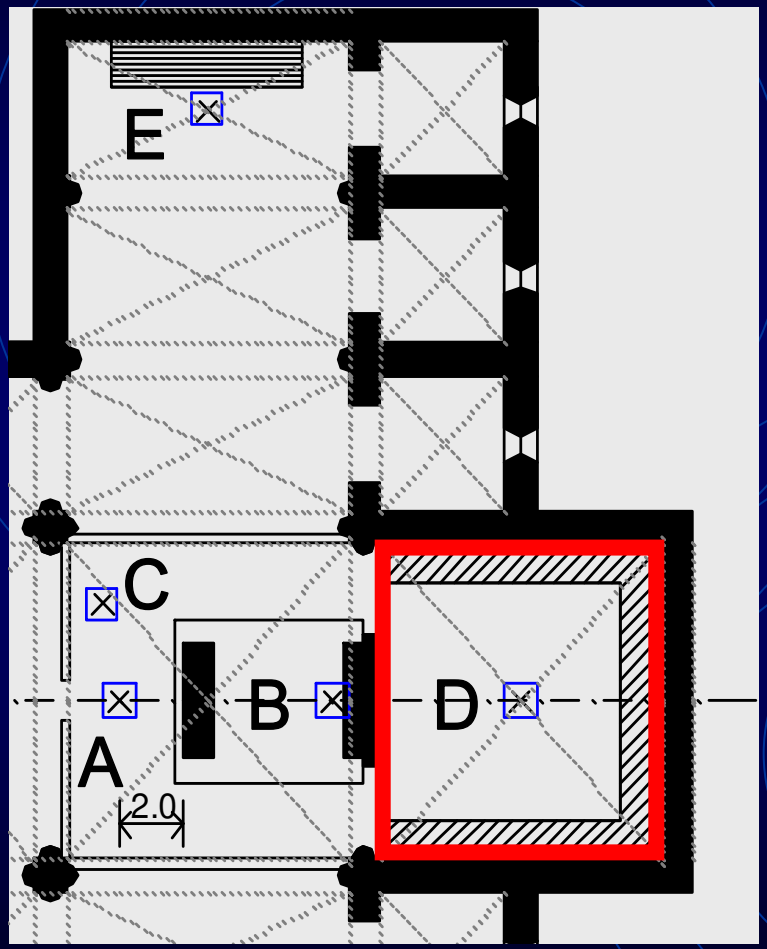
- B) High Altar position
  - At 1 m distance from the vertical surface
  - On the symmetry axis (provided that no focussing effects may be detected)
  - At 1.5 m from the basament of the altar

Source placement



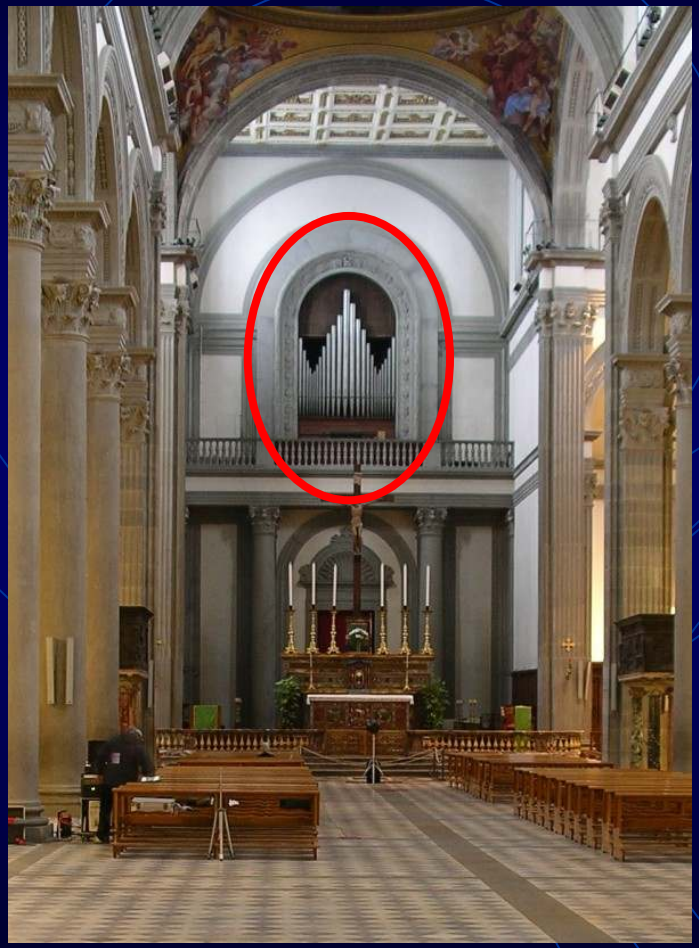
- C) Ambos position
  - Located at the symmetrical position opposite the actual ambos (to prevent interference)
  - or at 2 m from the edge of the chancel
  - At 1.5 m from the floor

Source placement



- D) Choir position
  - Located at the centre of the area occupied by the singers
  - or at the centre of the wooden stalls
  - in any case the source must be at least 1 m far from walls
  - the height must be 1.5 m from the floor

Source placement

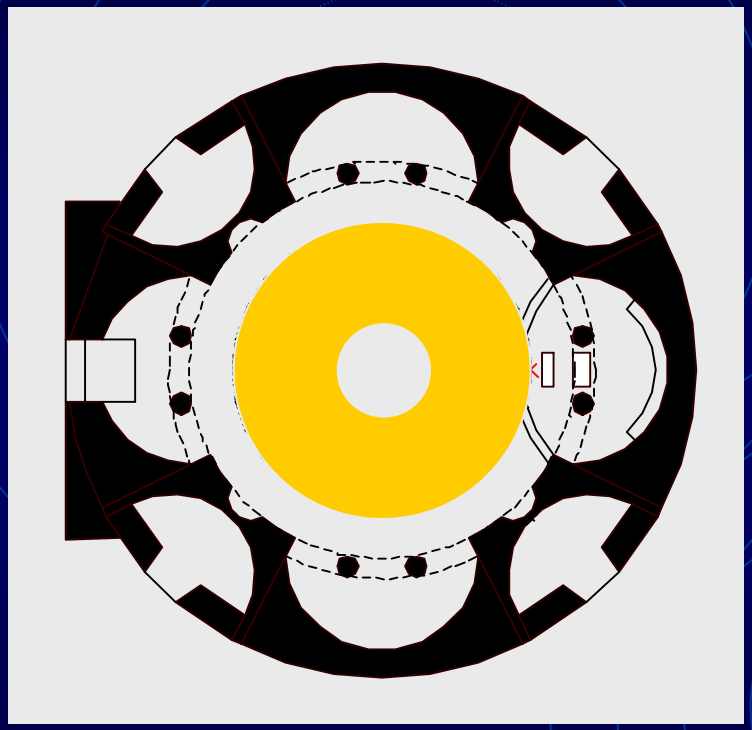


- E) Organ position
  - Located close to the centre of the organ pipes, at a distance of 1 m
  - If the span of the pipes is larger than 6 m 2 positions (E1 and E2) should be used
  - If the centre of the pipes cannot be reached the source height must be 2 m from the floor

Source placement

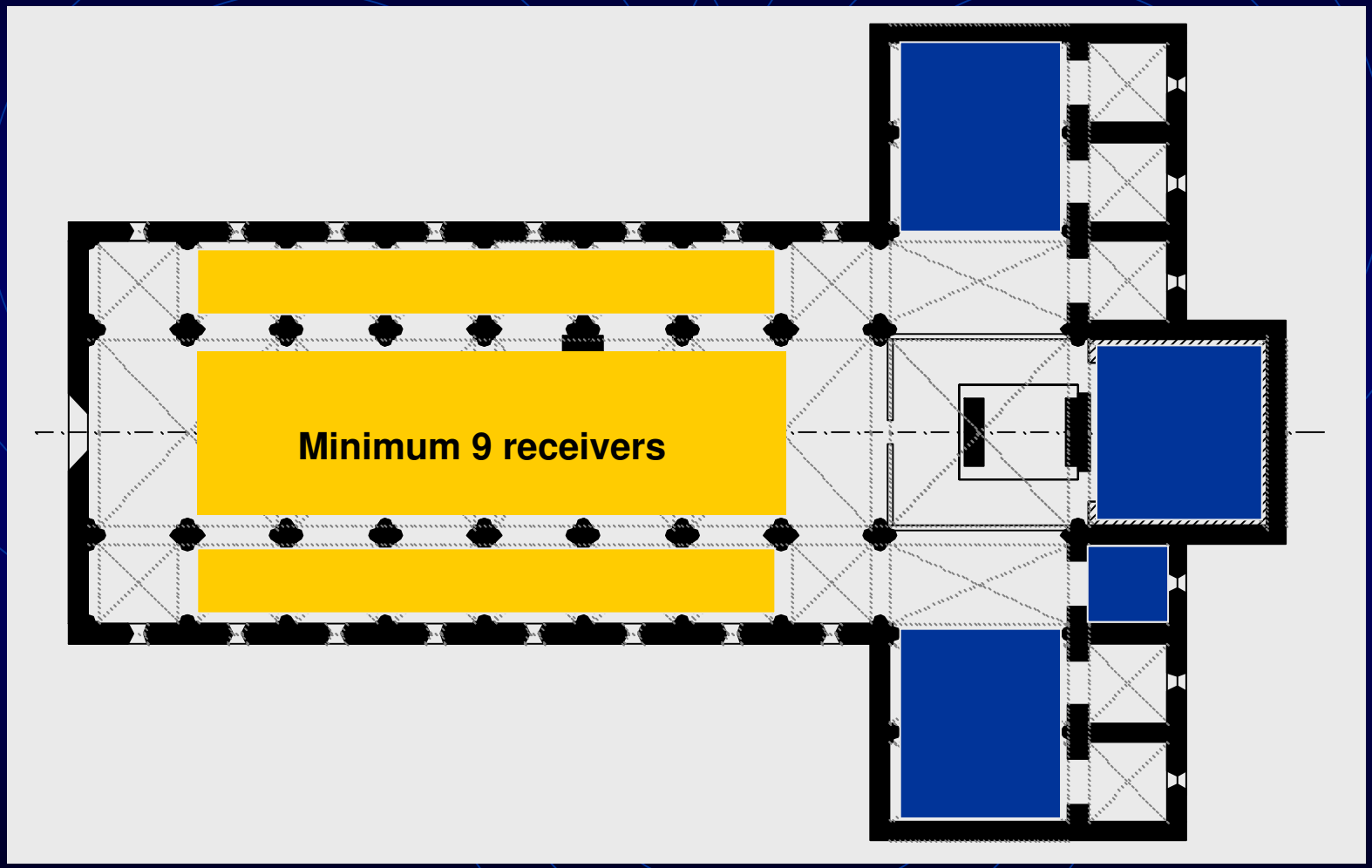
- F) Pulpit position
  - Located on the pulpit, provided that it is easily accessible
  - The source height should be at least 1.7 m and, in any case overcame the balustrade by at least 0.5 m
  - The source directivity should be close to human voice

Source placement

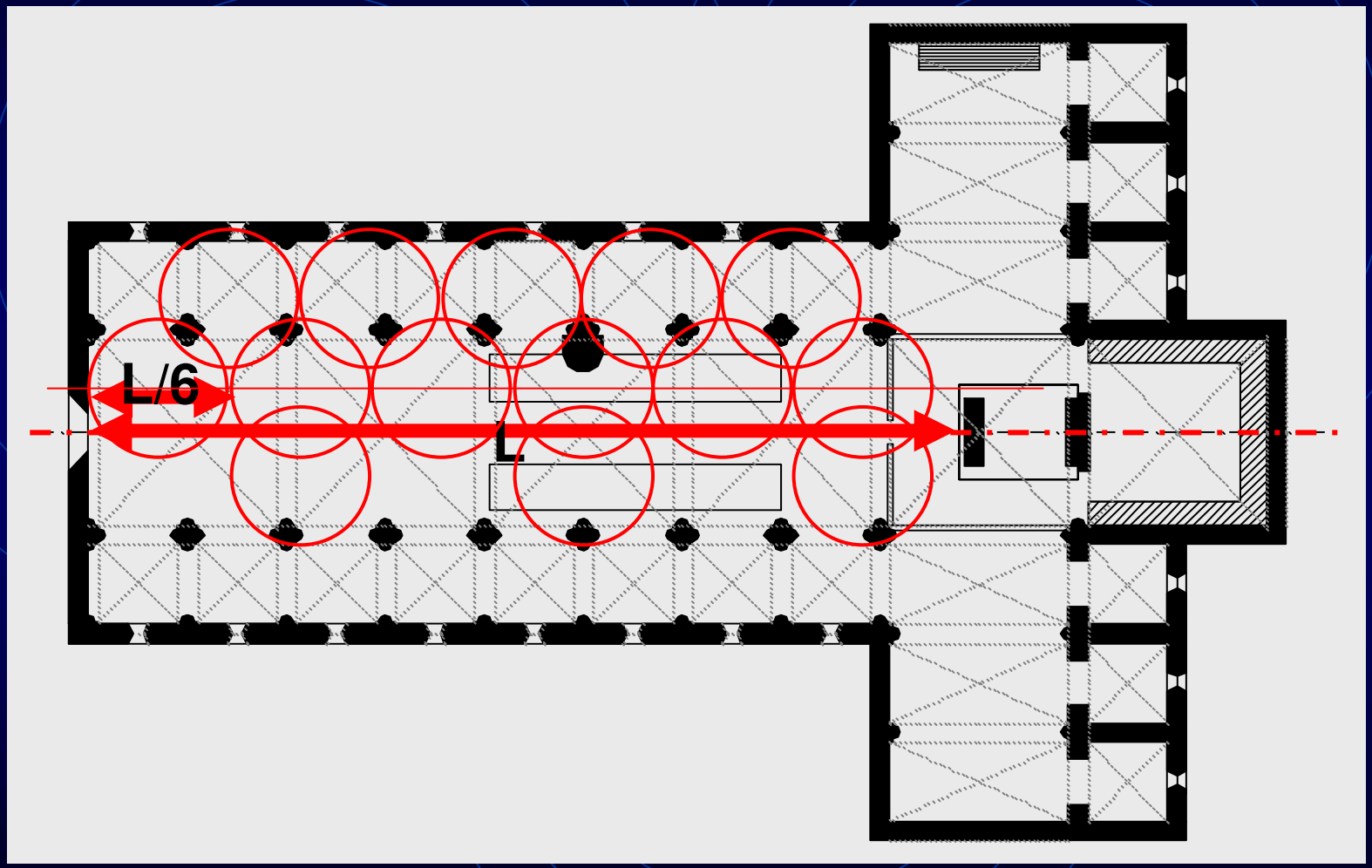


- G) Dome position
  - Located 1 m off the axis of the church
  - 2m from the centre of the dome
  - 2 m within the projection of the dome
  - 1.5 m from the floor

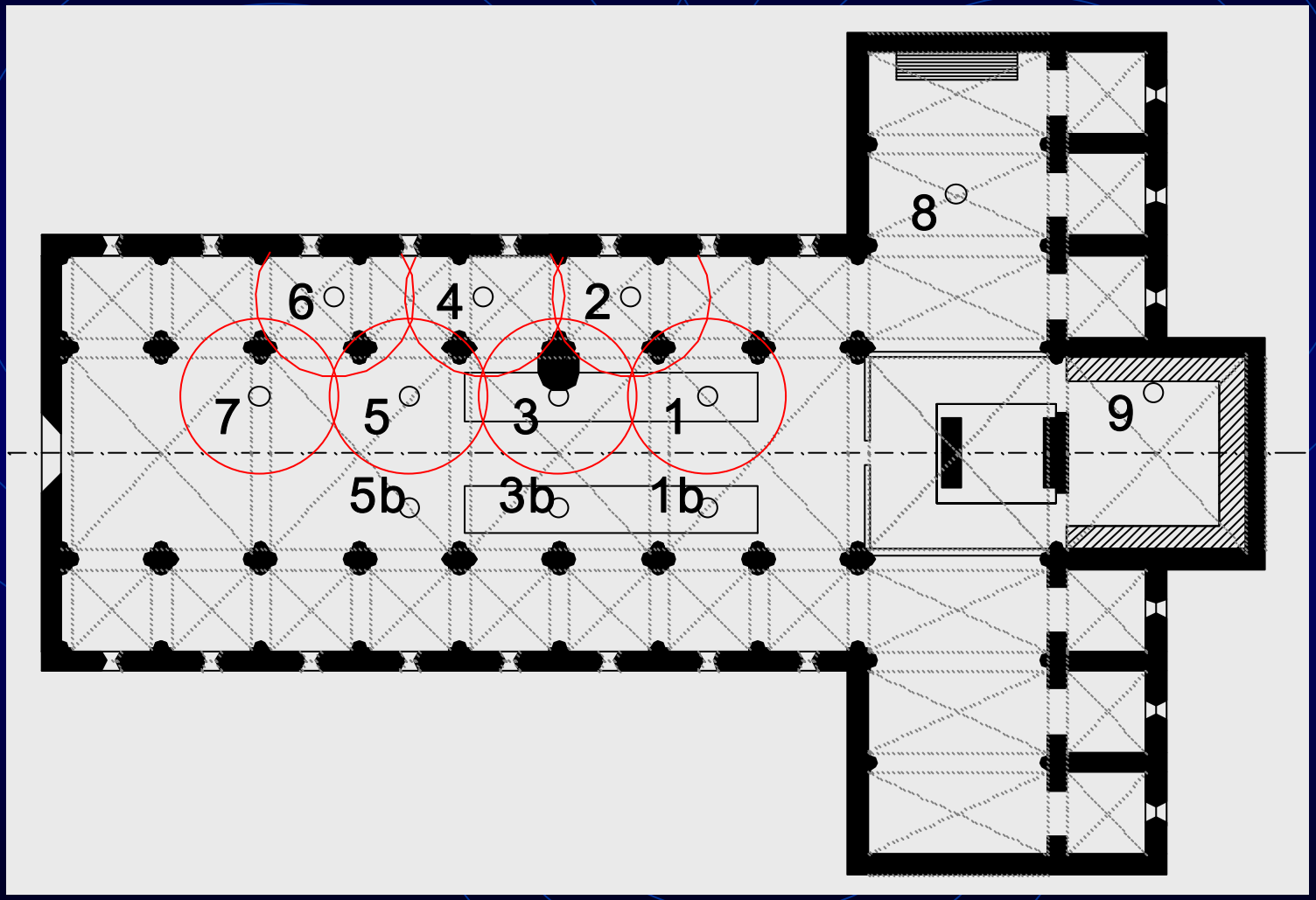
Receivers placement



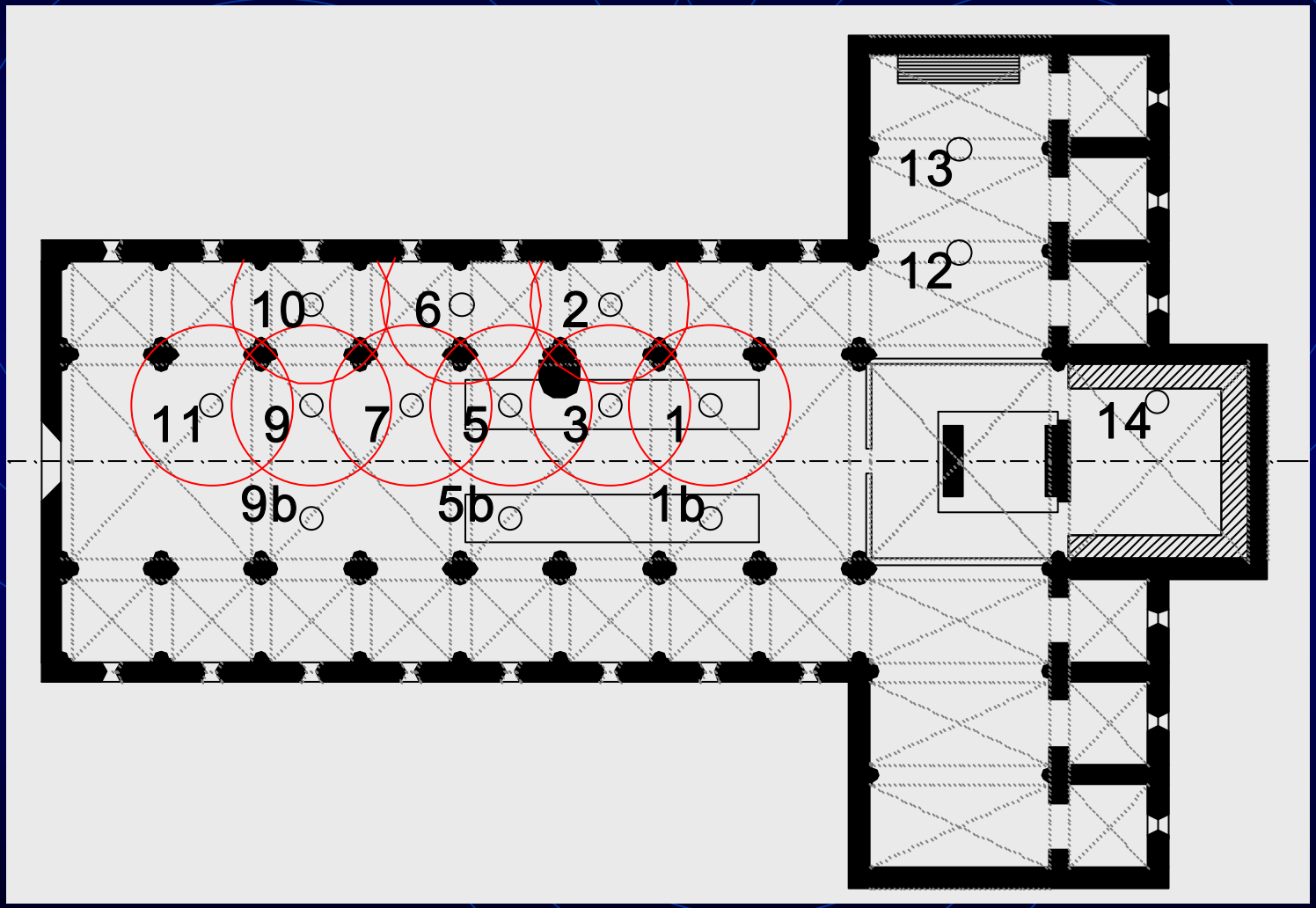
Receivers placement



Receivers placement



Receivers placement



Source and receiver combinations

Source	*Receivers in the main volume*	*Receivers in secondary volumes*
A, altar	All + 3 control rec.	All
B, high altar	50% + 2 control rec.	At least one in the same “volume” where the source is located
C, ambos		
D, choir		
E, organ		
F, pulpit	50% + 3 control rec.	None
G, dome	50%	At least 5 receivers under the dome
H…Z, extra	50%	At least one in the same volume where the source is located

Measurement equipment

	Basic	*Intermediate*	*Advanced*	*Rendering*
Sound source	Every source complying with ISO 3382	Electro-acoustic omni-directional	Electro acoustic, omni-directional + sub-woofer	Same as Advanced, Lw>100 dB if V> 50000 m^3
Signal	Noise, impulse, deterministic	Deterministic (MLS, sweep)	Deterministic (MLS, sweep) preferably equalized	Same as Advanced, but constant amplitude equalized sweep is preferred
Microphones	Omni-directional	Omni + figure8	Omni+figure8 (or B-format) + dummy head	B-format + dummy head
Freq. Range (Hz)	125-4000	125-4000	63-8000	63-16000
Sampling	44.1 kHz, 16 bit	44.1 kHz, 16 bit	44.1 kHz, 16 bit	48 kHz, 24 bit
Measurable parameters	T30, EDT and, with restrictions on the source, C, D, Ts, G	T30, EDT, C, D, Ts, G, LF, LG	T30, EDT, C, D, Ts, G, LF, LG, IACC	All